FR-23115
29 October 1993

ADVANCED LAUNCH SYSTEM ADVANCED DEVELOPMENT OXIDIZER TURBOPUMP PROGRAM

FINAL REPORT

Prepared Under
NASA Contract NAS8-37595
DRL Sequence No. 24

Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, AL 35812

Prepared by
Pratt & Whitney
Government Engines & Space Propulsion
P. O. Box 109600
West Palm Beach, Florida 33410-9600

(NASA-CR-193920) ADVANCED LAUNCH SYSTEM. ADVANCED DEVELOPMENT OXIDIZER TURBOPUMP PROGRAM Final Report (PWA) 294 p

N94-25174

Unclas

G3/37 0207560

UNITED TECHNOLOGIES
PRATT & WHITNEY

TABLE OF CONTENTS

1.0 INTRODUCTION

On May 19, 1989, Pratt & Whitney was awarded contract NAS8-37595 by the National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville Alabama for an Advanced Development Program (ADP) to design, develop and demonstrate a highly reliable low cost, liquid oxygen turbopump for the Advanced Launch System (ALS).

The ALS had an overall goal of reducing the cost of placing payloads in orbit by an order of magnitude. This goal would require a substantial reduction in life cycle costs, with emphasis on recurring costs, compared to current launch vehicles. Engine studies supporting these efforts were made for the Space Transportation Main Engine (STME). The emphasis on low cost required design simplification of components and subsystems such that the ground maintenance and test operations was minimized. The results of the Oxygen Turbopump ADP technology effort would provide data to be used in the STME. Initially the STME baseline was a gas generator cycle engine with a vacuum thrust level of 580,000 lbf. This was later increased to 650,000 lbf and the oxygen turbopump design approach was changed to reflect the new thrust level.

It was intended that this ADP program be conducted in two phases. Phase I, a basic phase, would encompass the preliminary design effort, and Phase II, an optional contract phase to cover design, fabrication and test evaluation of an oxygen turbopump at a component test facility at the NASA John C. Stennis Space Center in Mississippi.

The basic phase included preliminary design and analysis, evaluation of low cost concepts, and evaluation of fabrication techniques.

The option phase included design of the pump and support hardware, analysis of the final configuration to ensure design integrity, fabrication of hardware to demonstrate low cost, DVS Testing of hardware to verify the design, assembly of the turbopump and full scale turbopump testing.

In December 1990, the intent of this ADP to support the design and development was changed. The design effort for the oxygen turbopump became part of the STME Phase B contract. The status of the pump design funded through this ADP was presented at the Preliminary Design Review (PDR) at the MSFC on October 24, 1990. Advancements in the design of the pump were subsequently continued under the Phase B Contract. The emphasis of this ADP became the demonstration of individual technologies that would have the greatest potential for reducing the recurring cost and increasing reliability.

In October of 1992, overall program funding was reduced and work on this ADP was terminated.

2.0 KEY ACCOMPLISHMENTS

A summary of accomplishments on this program includes completion of a series of trade studies based on reliability and low cost. Over twenty cross section drawings of oxygen turbopump unique designs were evaluated. A preliminary cost model was defined, many manufacturing processes were evaluated and several demonstrated, and various materials were evaluated and characterized

TQM processes were utilized throughout the preliminary design to ensure optimization of a low cost, highly reliable, robust design.

2.1 TRADE STUDIES

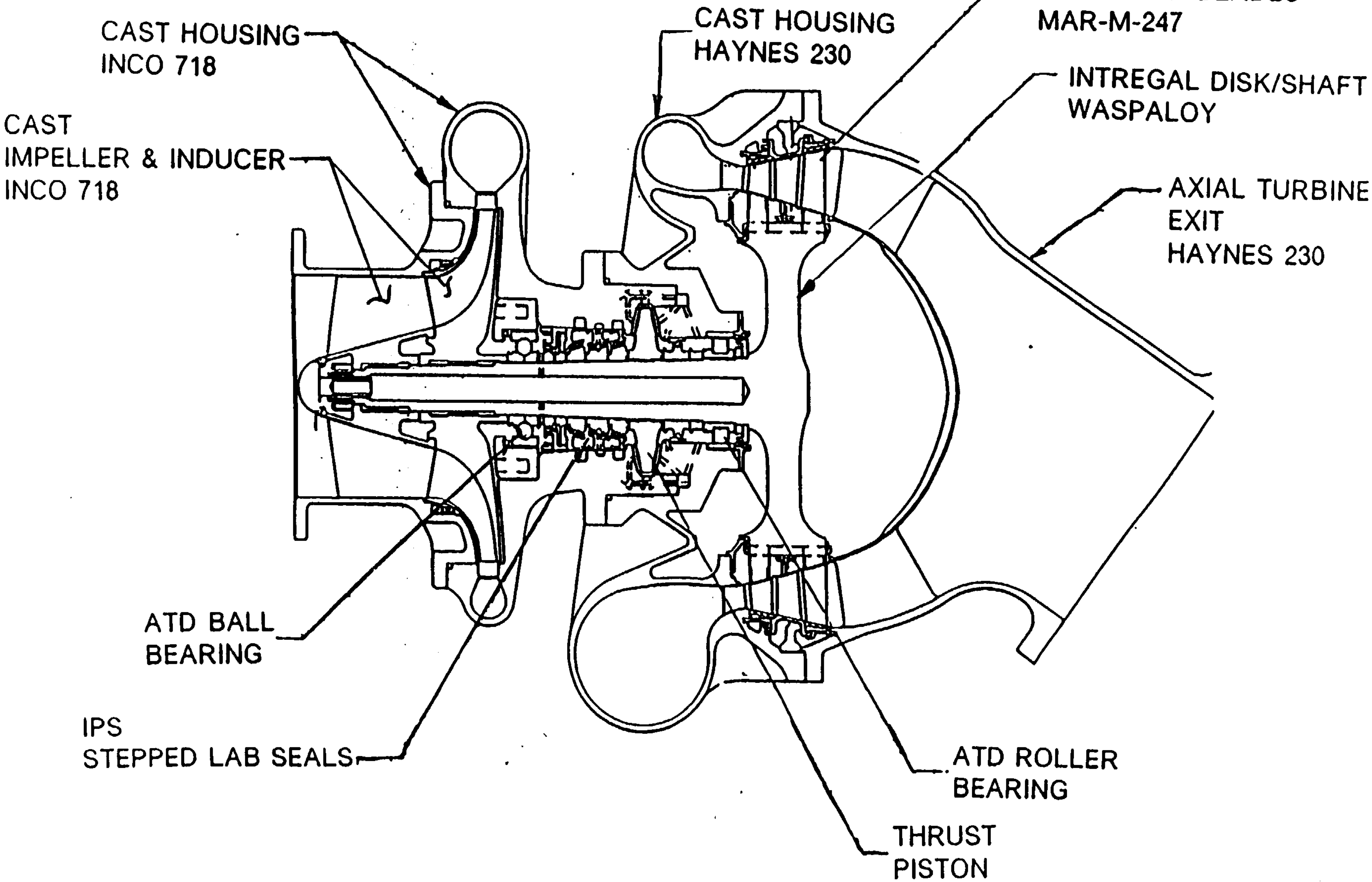
The objective of the trade studies was to define a highly reliable oxygen turbopump, featuring low production and operating costs. These trade studies were conducted for both the design and fabrication process. Sections 2.1.1 and 2.1.2 contain an overview of the trade studies conducted.

2.1.1 DESIGN TRADES

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

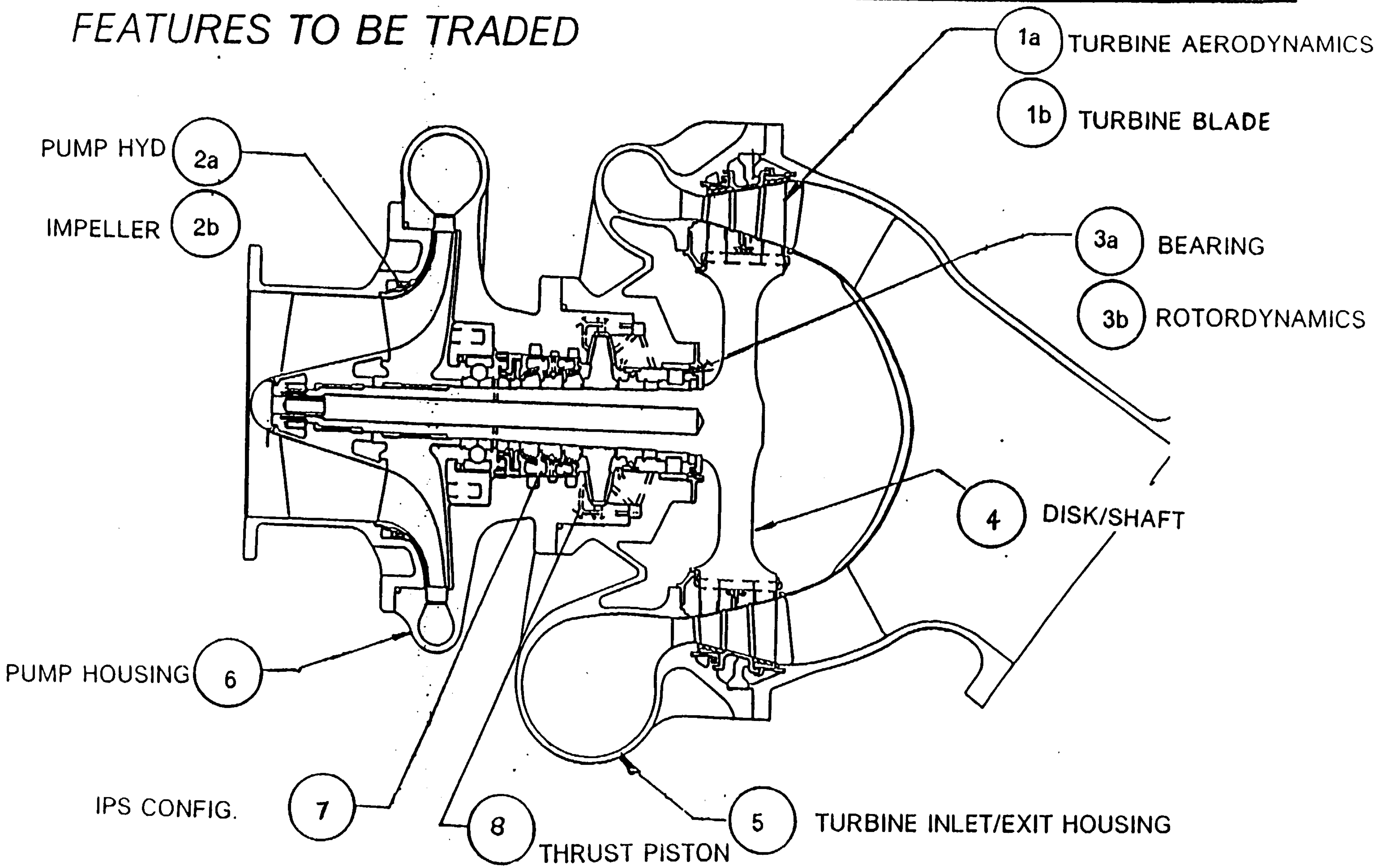
INITIAL PROPOSAL CONFIGURATION



UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

FEATURES TO BE TRADED



UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1a-TURBINE AERODYNAMICS

SINGLE STAGE	SHROUDED	SOLID	ELIMINATED TO THIS POINT
		HOLLOW	
	UNSHROUDED	SOLID	
		HOLLOW	
TWO STAGE (SAME # OF BLADES / STG)	SHROUDED	UNIQUE AERO	SOLID
			HOLLOW
		COMMON AERO	SOLID
			HOLLOW
	UNSHROUDED	UNIQUE AERO	SOLID
			HOLLOW
		COMMON AERO	SOLID
			HOLLOW

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1a - TURBINE AERODYNAMICS

- RESOLVED:
  - SINGLE STAGE TURBINES ELIMINATED DUE TO HIGH HOUSING COSTS DRIVEN BY THE SIGNIFICANTLY LARGER DIAMETERS OF BLADE HOUSING

    -SINGLE STAGE REDUCES TOTAL NUMBER OF BLADES BY APPROXIMATELY 30, ELIMINATES ONE VANE RING

    -LOWER A/F COSTS SURPASSSED BY HIGHER HOUSING COSTS
  - SOLID AIRFOILS ELIMINATED DUE TO THE LARGER MAX AIRFOIL THICKNESSES DRIVEN BY THE MEAN VELOCITY RATIOS REQUIRED

    -INCREASED PULL DUE TO SOLID A/F'S MAKES ATTACHMENT DESIGN DIFFICULT

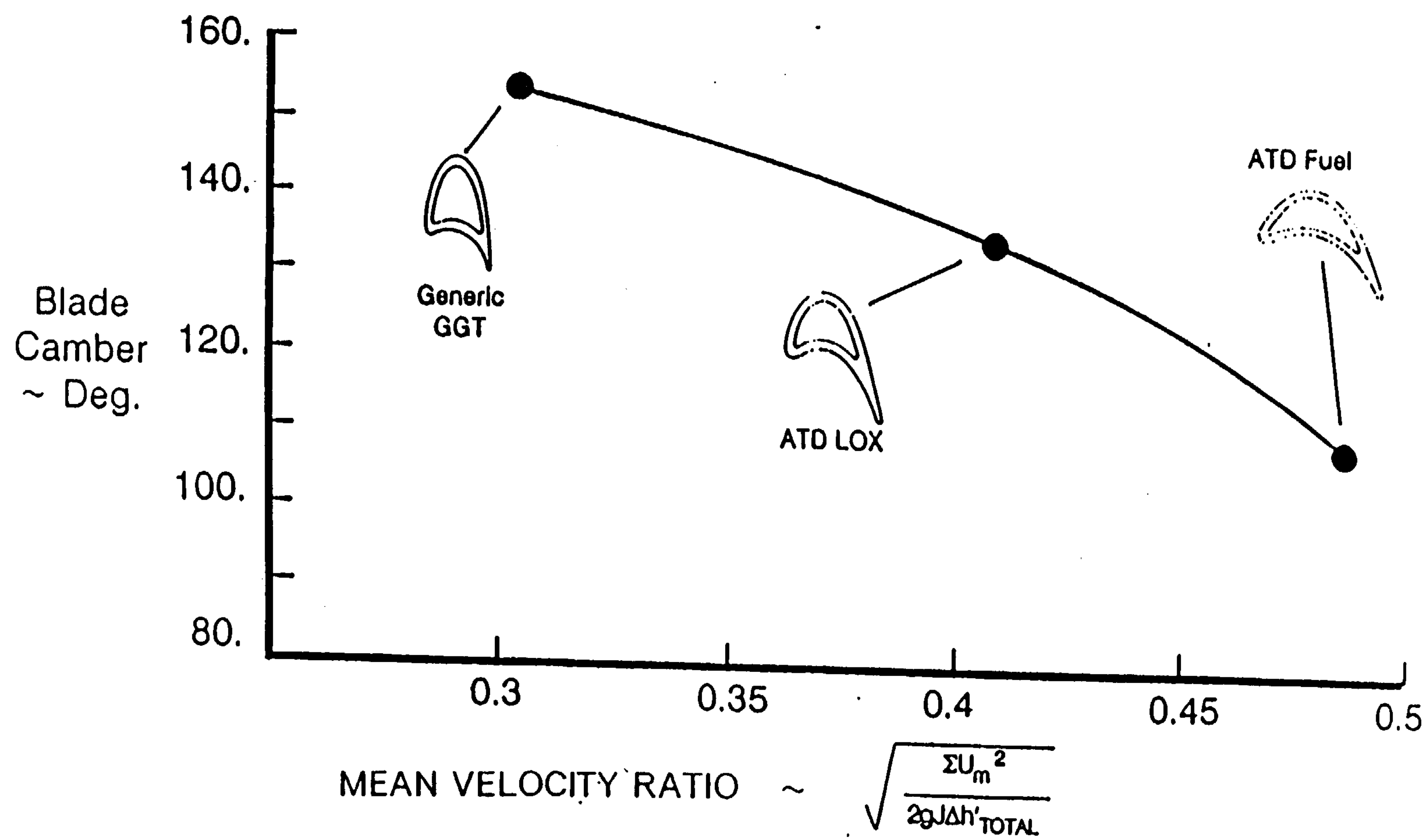
    -HOWMET (WICHITA FALLS) QUOTES 15-20% COST INCREASE FOR HOLLOW AIRFOILS

    -USE OF HOLLOW A/F'S ELIMINATES FORGED BLADES FROM CONSIDERATION

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

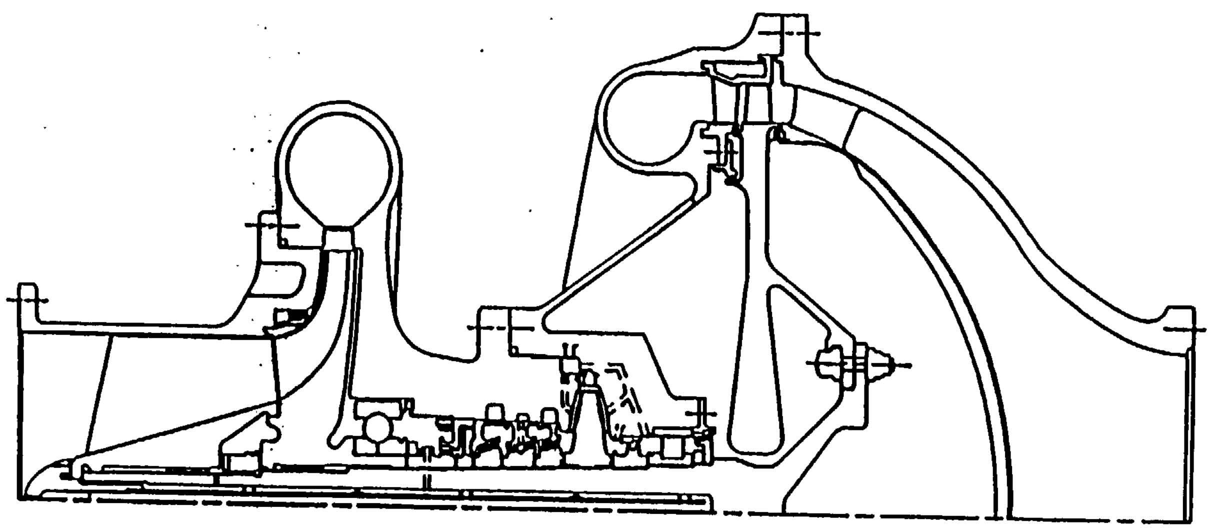
REDUCED VELOCITY RATIO INCREASES BLADE TURNING REQUIREMENTS



UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

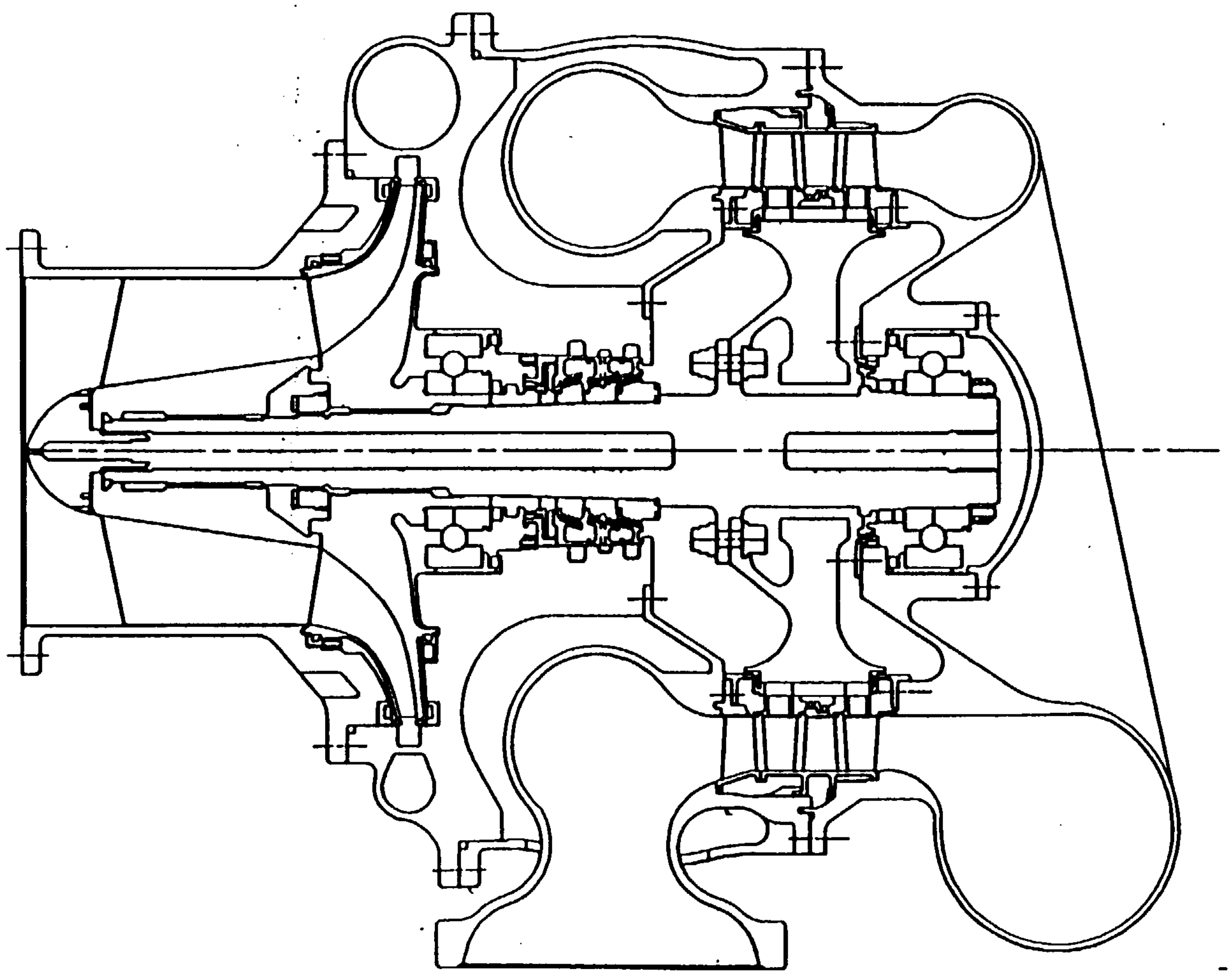
ITEM 1a - TURBINE AERODYNAMICS



SINGLE STAGE TURBINE

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1a - TURBINE AERODYNAMICS



TWO STAGE TURBINE

UNITED TECHNOLOGIES PRATT & WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 12 - TURBINE AERODYNAMICS

- REMAINING TO BE DONE:
    - REDUCED NUMBER OF BLADES PER STAGE AND EFFECT ON COST
    - COMMON AERO
    - SUPERSONIC AERO

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

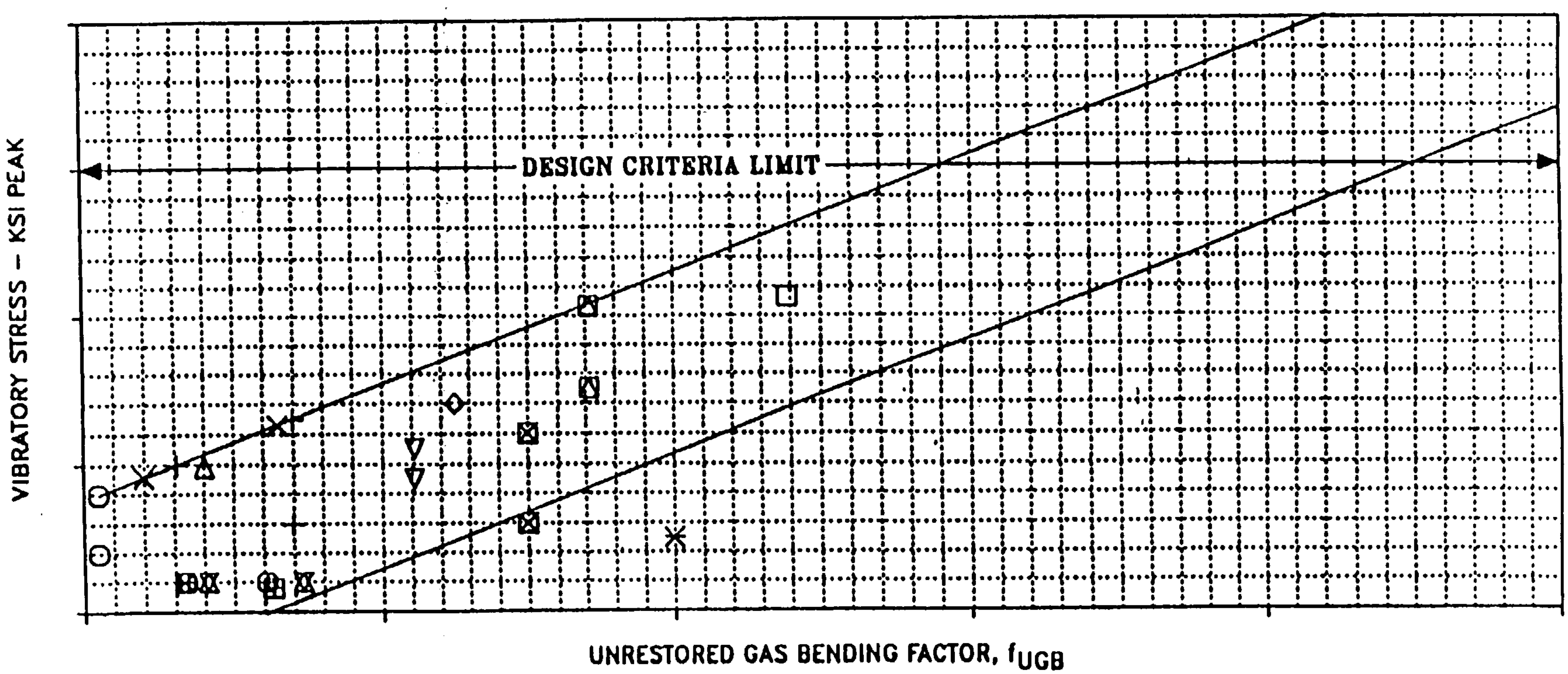
ITEM 1b - TURBINE BLADE

TRADES TO BE PERFOMED:

- FIRTREE VERSUS DOVETAIL
  - -MACHINING COSTS ABOUT EVEN ? - YES
  - -LOW STRESS LEVELS MAKE DOVETAIL POSSIBLE,KNOWN LOAD SPLIT
  - -INVESTIGATE USING EXISTING FIRTREE TO ELIMINATE TOOLING COSTS OR ALLOW BLOOM GRINDING
- AS COST BLADES VS MINIMAL MACHINING VS TRADITIONAL MACHINING
  - -COST VERSUS PERFORMANCE
- DAMPED VERSUS UNDAMPED BLADES
- SHROUDED VS UNSHROUDED

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1b - TURBINE BLADE

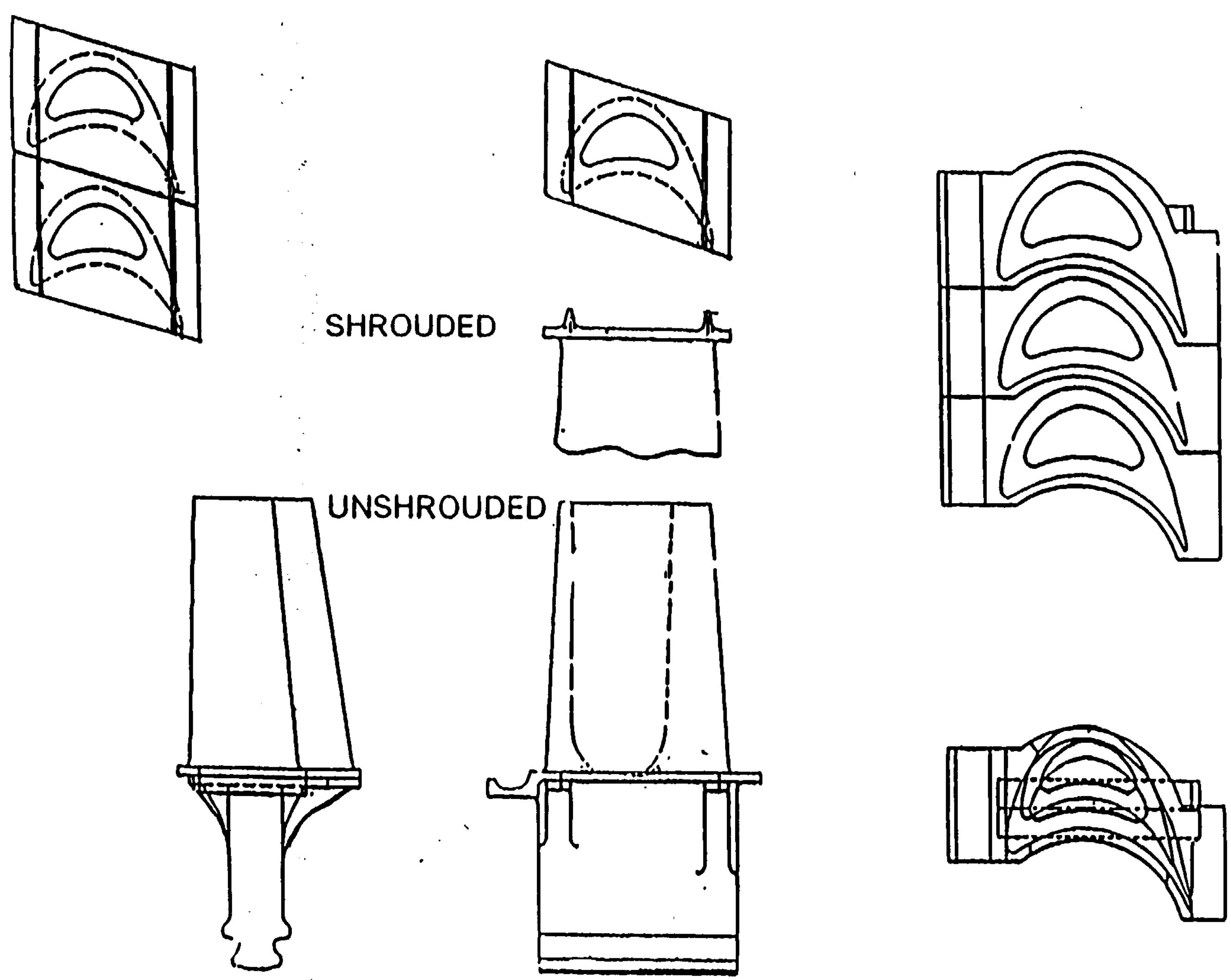


BLADE DAMPING EXPERIENCE

UNITED TECHNOLOGIES
PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1B - TURBINE BLADE



UNITED TECHNOLOGIES PRATT&WHITNEY

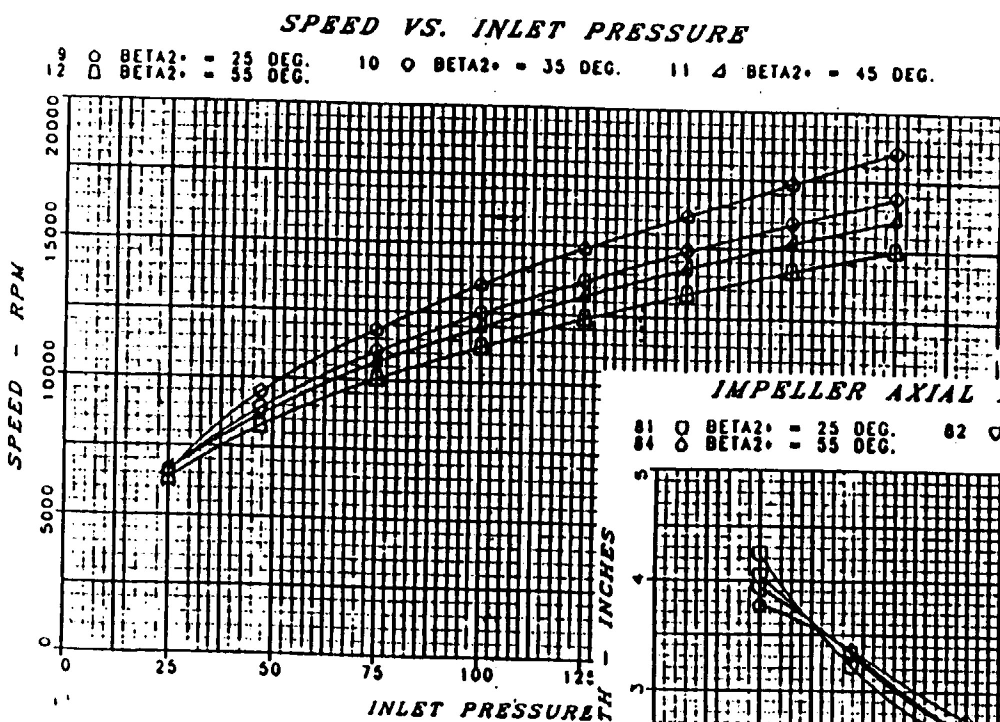
ADP OXYGEN TURBOPUMP TRADE STUDIES

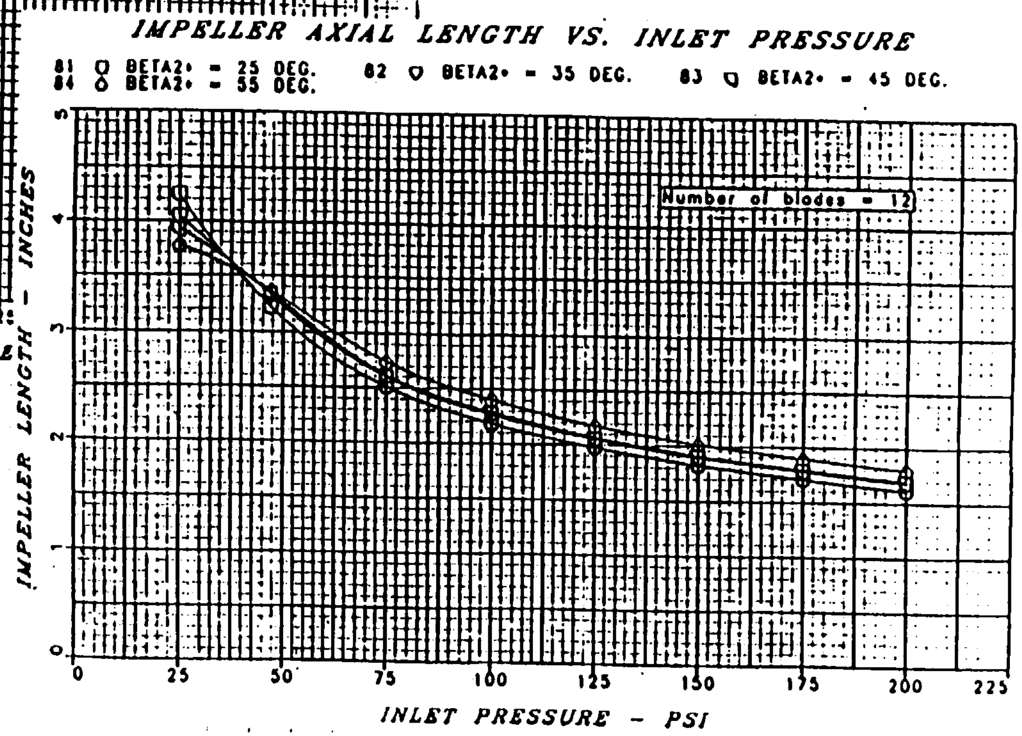
ITEM 2a - PUMP HYDRODYNAMICS

- TRADES COMPLETED
  - *Inlet Pressure*
  - *Impeller Discharge Blade Angle*
  - *No. Impeller Blades*
  - *Pump Speed*

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 2 - PUMP HYDRODYNAMICS





UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 2b - IMPELLER

- TRADES TO BE DONE
  - PERFORMANCE EFFECTS OF:
    - SURFACE FINISH
    - BLADE TOLERANCES
    - BLADE THICKNESSES
  - FABRICATION OPTIONS:
    - INTREGALLY CAST HUB AND SHROUD
    - POWDER METAL INTREGAL HUB AND SHROUD USING THE ROC PROCESS
    - FORGED HUB WITH DIFFUSION BONDED SHROUD
    - FORGED HUB WITH CAST SHROUD

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 3a - BEARINGS

- USE SSME/ATD BEARINGS
    - \+ • PREVIOUSLY DEVELOPED
    - \+ • REDUCED DN
    - − • LIMITS SHAFT DIAMETER
    - − • LIMITS AXIAL LOAD CAPABILITY
    - − • LIMITS OPTIONS OF BRG POSITION (SHAFT TORQUE)

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 3a - BEARINGS

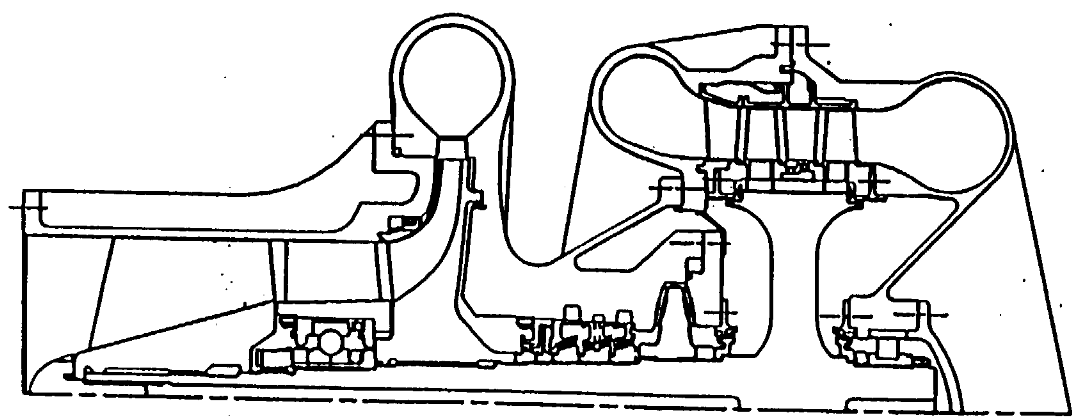
- USE NEW LARGER PITCH DIA BALL BEARING
  - \+ • SAME ROLLING ELEMENT SIZE AS ATD, JUST MORE OF THEM
  - \+ • INCREASED AXIAL LOAD CAPABILITY
  - \+ • INCREASED SHAFT DIAMETER CAPABILITY
  - \+ • HIGHER RADIAL LOAD CAPABILITY
  - \+ • POTENTIAL TO OPTIMIZE THE BEARING DESIGN FOR MAXIUM RADIAL LOAD CAPABILITY
  - \+ • UNRESTRICTED BRG POSITION
  - – • REQUIRES DESIGN & DEVELOPMENT OF A NEW BEARING
  - – • HIGHER DN (WITHIN EXPERIENCE)

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 3b - ROTORDYNAMICS

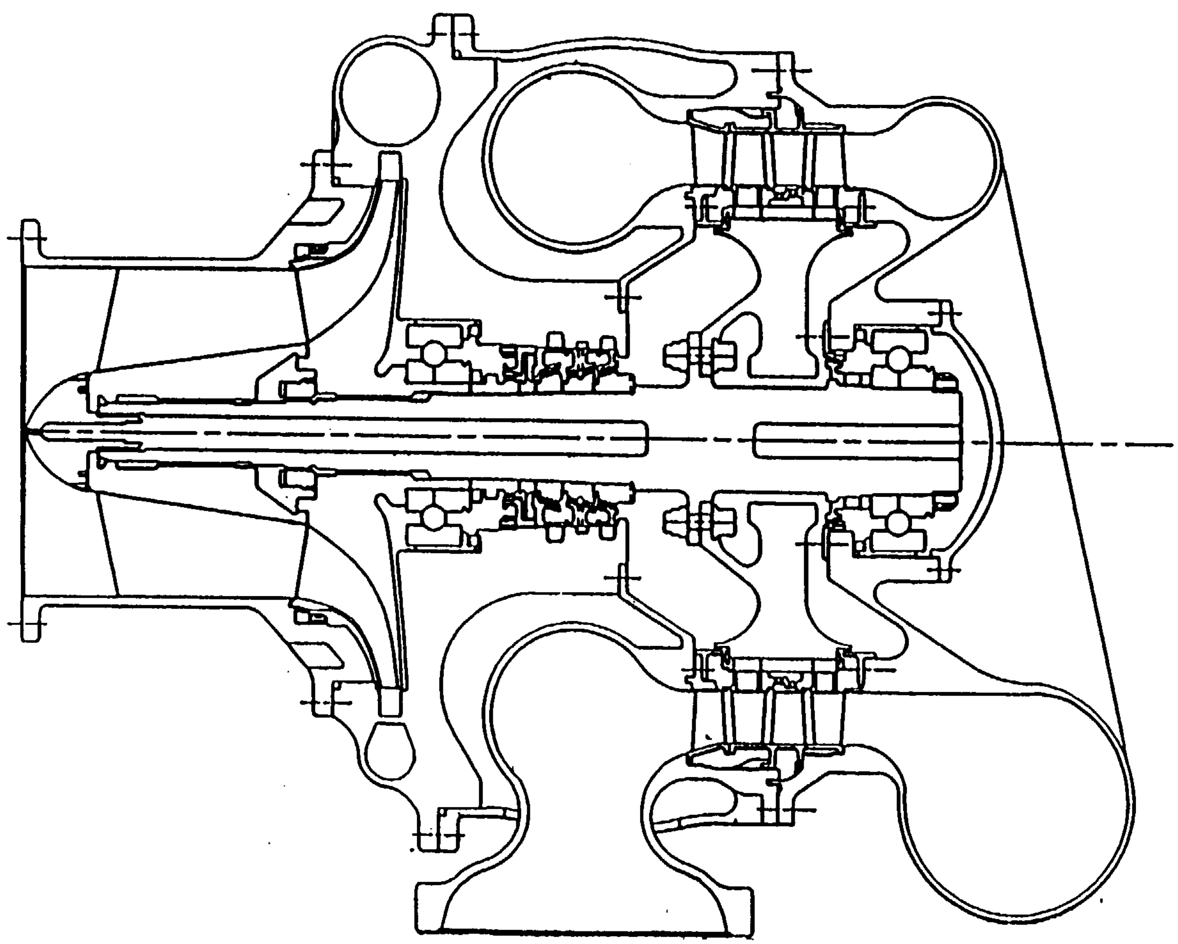
- 3 BASIC CONFIGURATIONS
  - ATD BALL/ROLLER - STRADDLED TRUBINE
  - NEW BALL/BALL - STRADDLED TURBINE
  - NEW BALL/BALL - OVERHUNG TURBINE



CONFIGURATION #1 - ATD BALL/ROLLER

ADP OXYGEN TURBOPUMP TRADE STUDIES

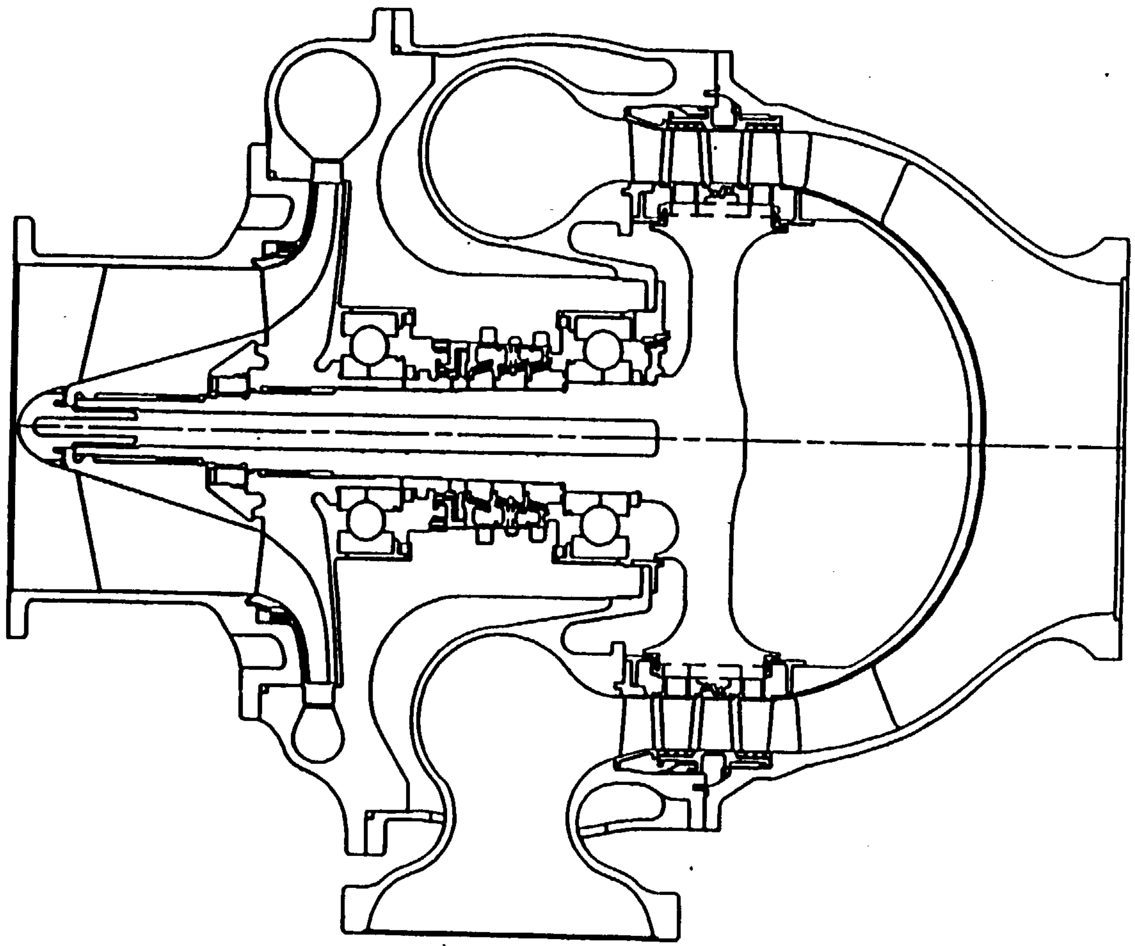
ITEM 3b - ROTORDYNAMICS



CONFIGURATION #2 - NEW BALL/BALL

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 3b - ROTORDYNAMICS



CONFIGURATION #3 - NEW BALL/BALL

UNITED TECHNOLOGIES PRATT&WHITNEY

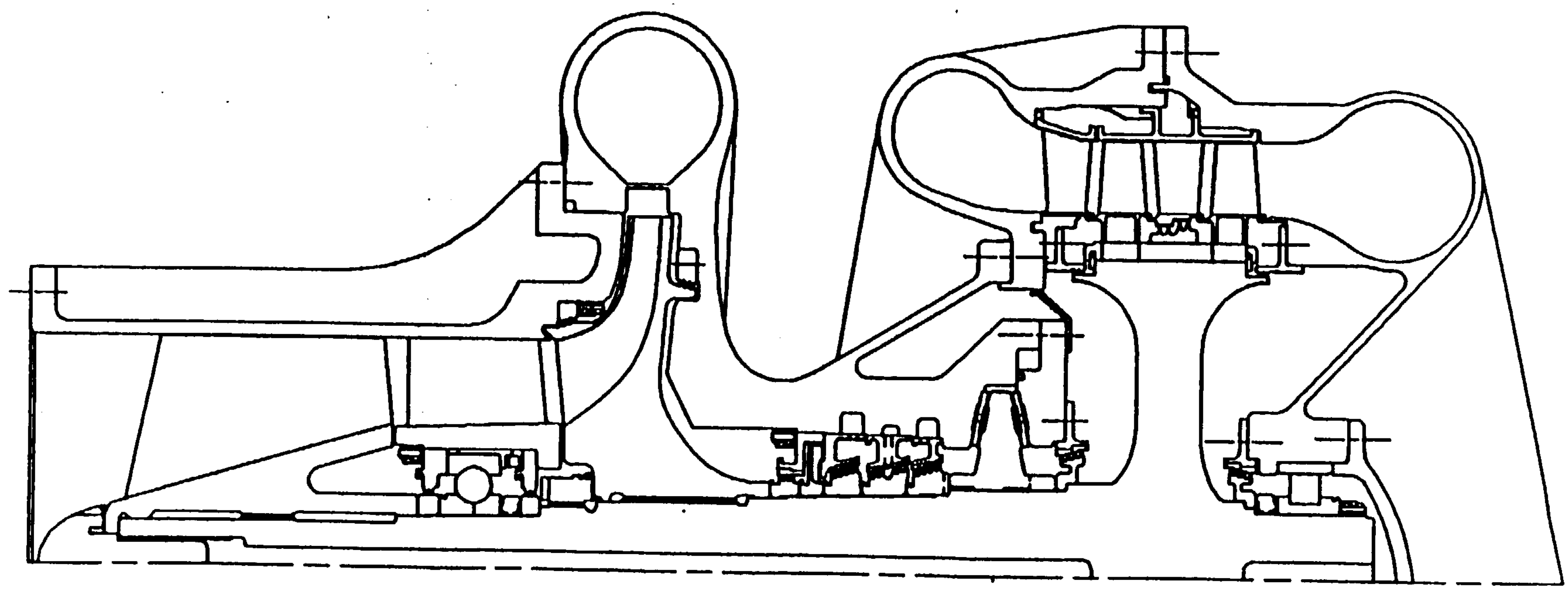
ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT

- INTREGAL DISK & SHAFT
- BOLTED DISK & SHAFT
- TWO INDIVIDUAL DISKS, BOLTED TO SHAFT
- IBR'S
- BLING (CAST BLADED RING, BONDED TO FORGED DISK)

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT

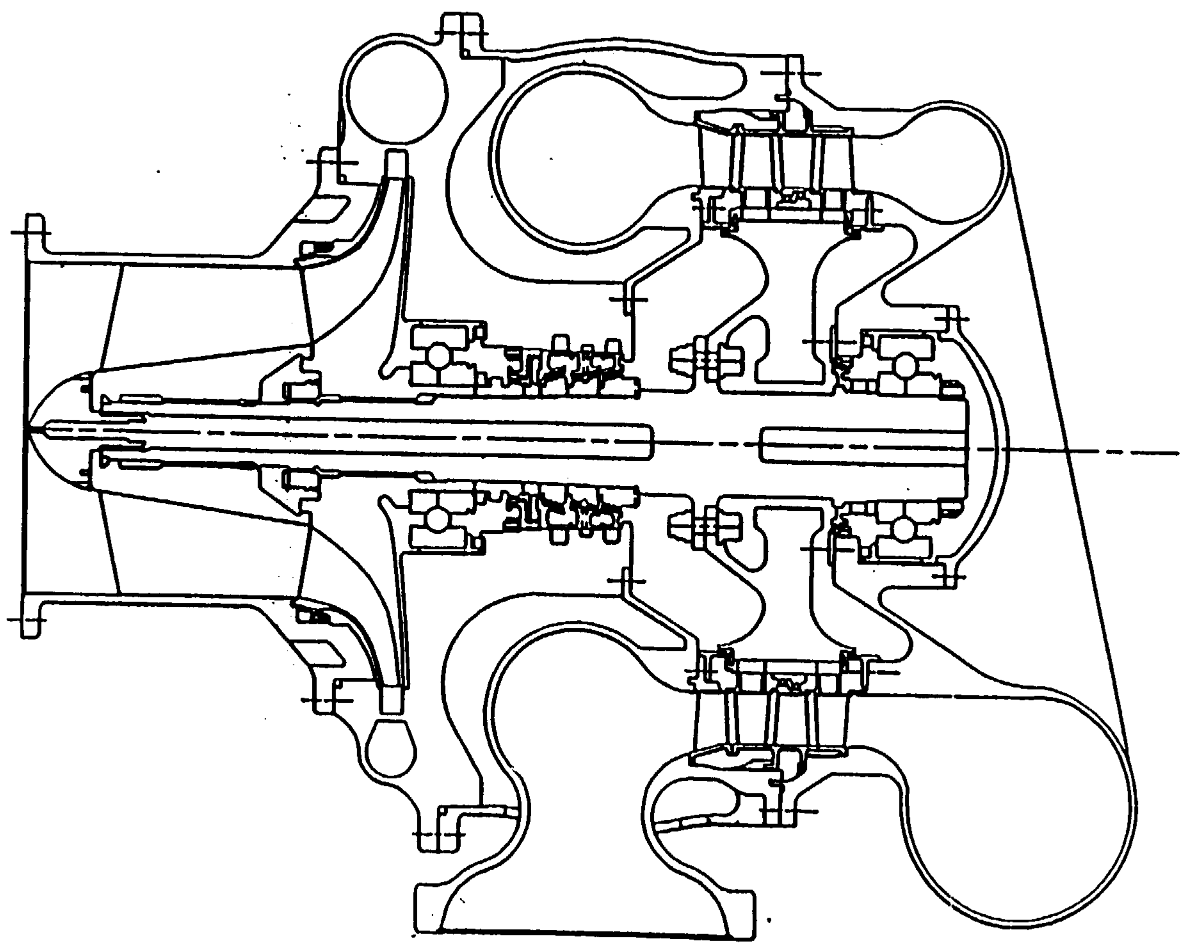


INTREGAL DISK AND SHAFT

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT

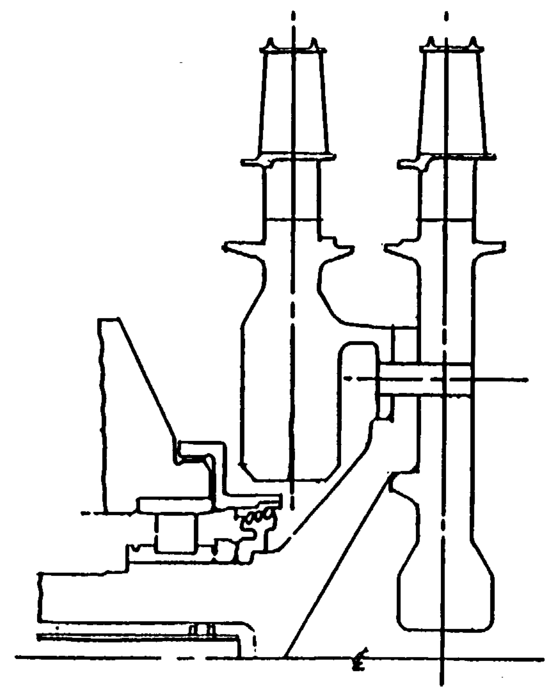


BOLTED DISK & SHAFT

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT

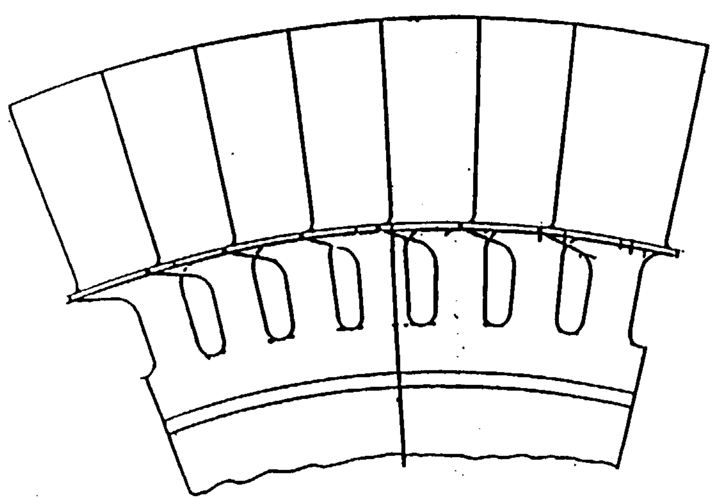


TWO INDIVIDUAL DISK, BOLTED TO SHAFT

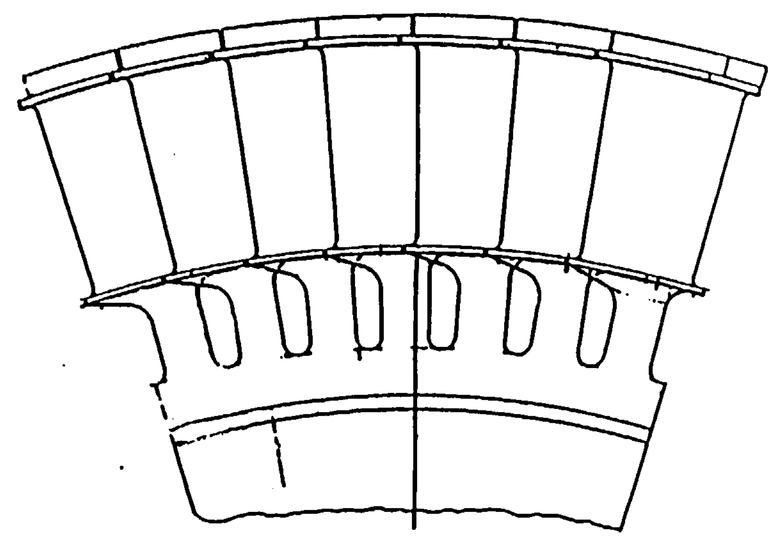
UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT



UNSHROUDED



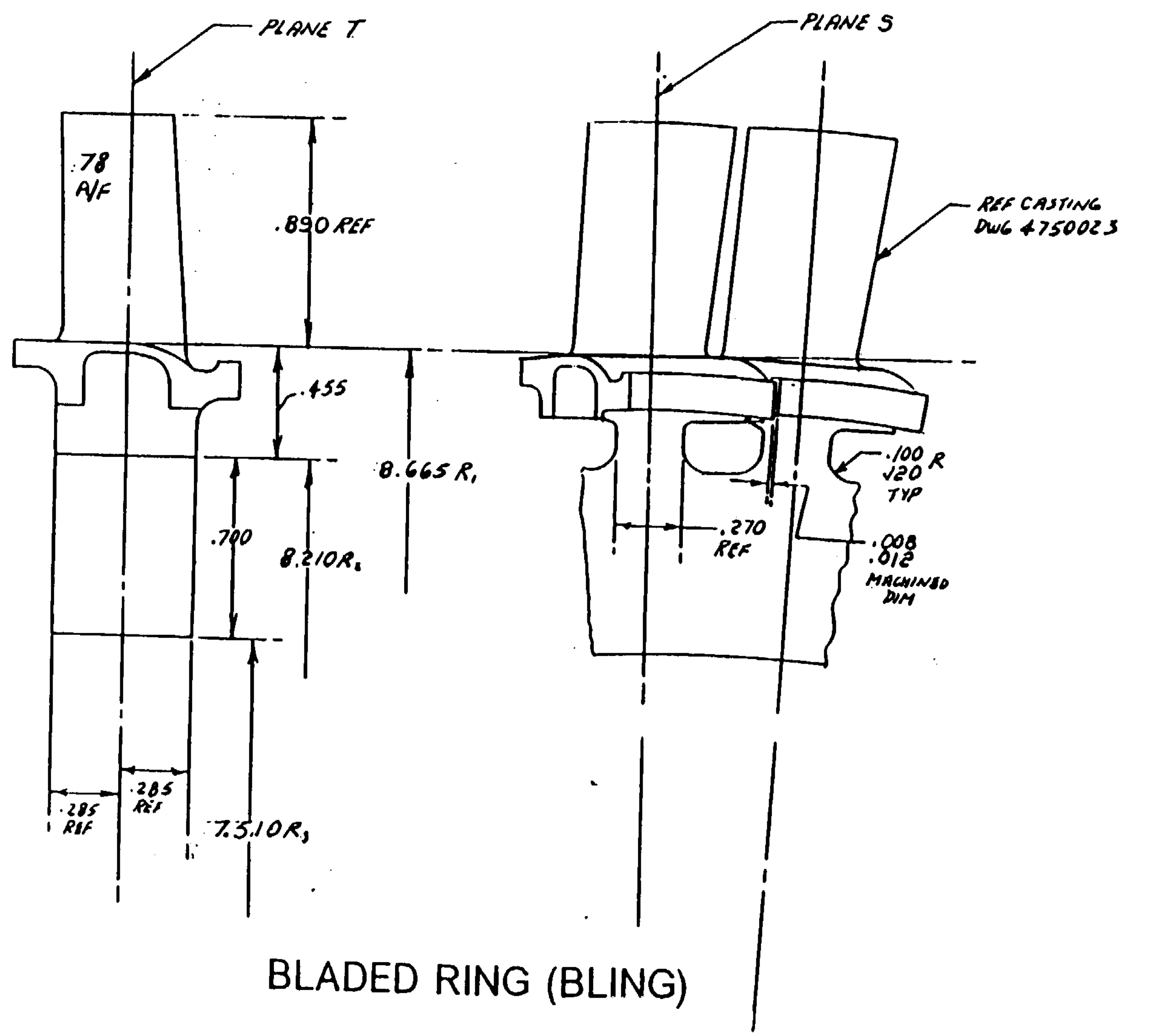
SHROUDED

INTEGRALLY BLADED ROTOR (IBR)

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK/SHAFT



BLADED RING (BLING)

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 4 - DISK /SHAFT SUMMARY

- RESOLVED (TOO COSTLY)
    - IBR'S & TWO INDIVIDUAL DISKS
- YET TO BE DONE
    - MATERIAL - A286 VS. WASPALOY
      - A286 IS PRIME - HYDROGYN RESISTANCE
    - INTREGAL DISK & SHAFT
        - COMPROMISED PROPERTIES? LIMITED TO SAME MAT'L
    - BOLTED DISK & SHAFT
        - ROTORDYNAMIC IMPACT?
        - DISK & SHAFT CAN BE DIFFERENT MAT'LS
        - BLING

UNITED TECHNOLOGIES
PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

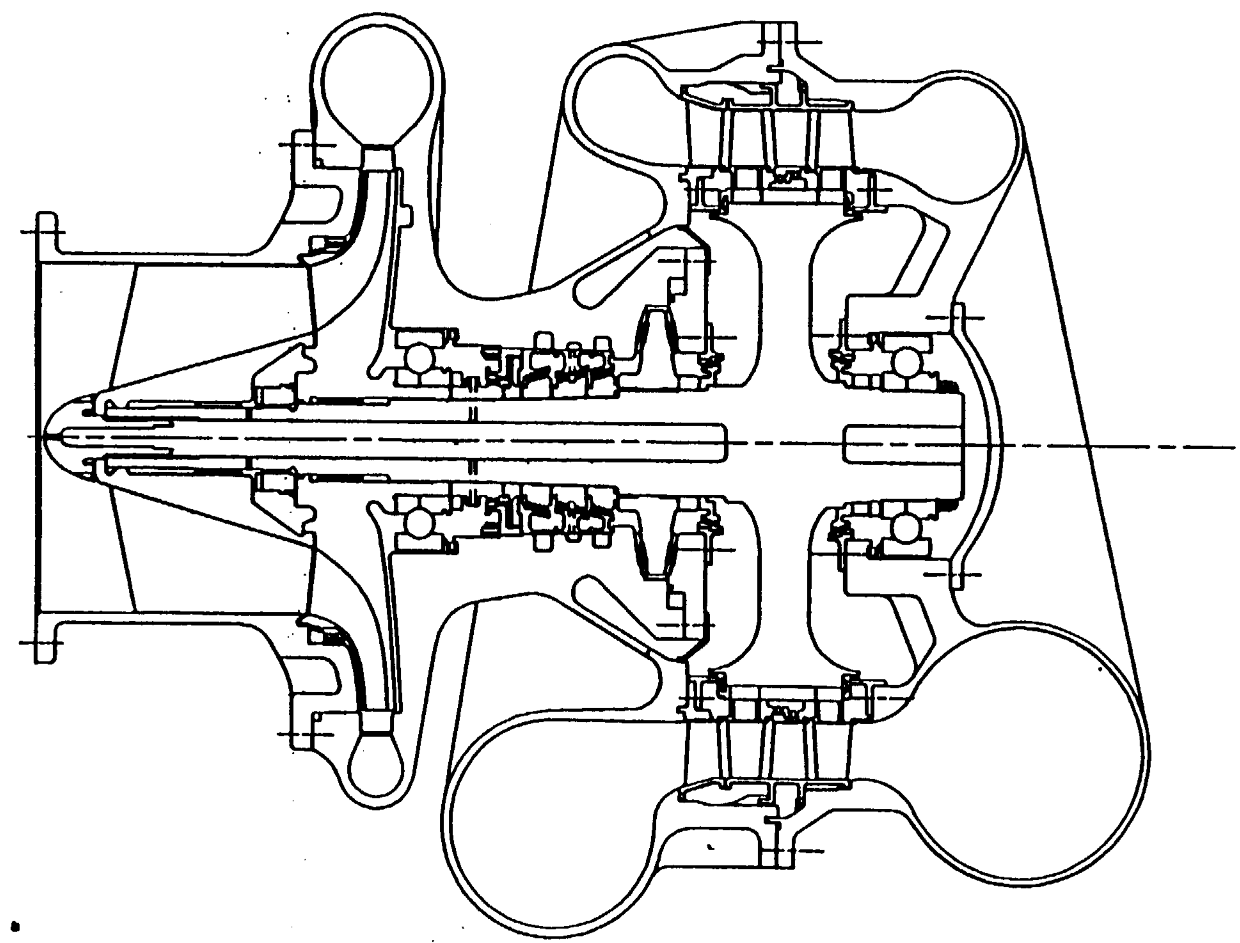
ITEM 5 - TURBINE INLET/EXIT HOUSING

- VOLUTE
- TORODIAL, CONSTANT AREA
- AXIAL
- REVERSE TRUBINE

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 5 - TURBINE INLET/EXIT HOUSING

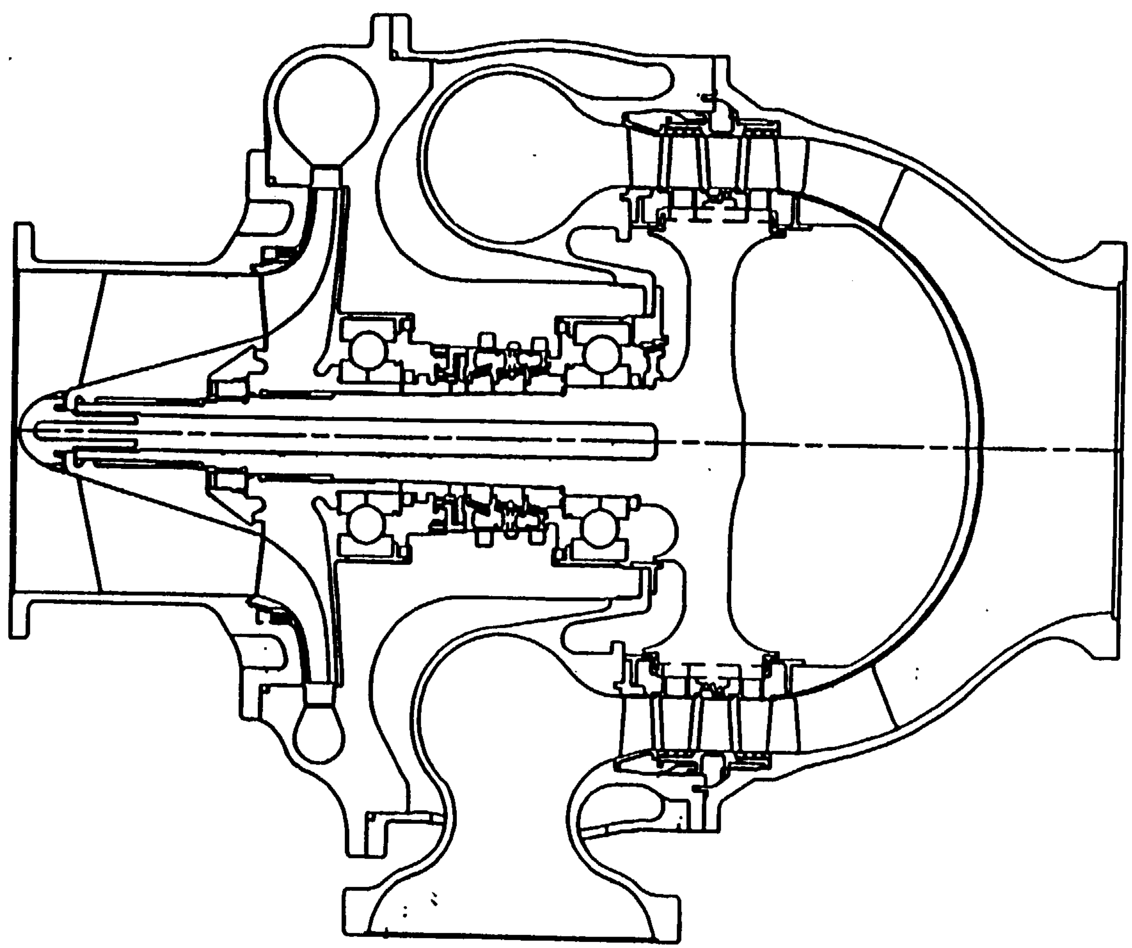


INLET: VOLUTE

EXIT: VOLUTE

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 5 - TURBINE INLET/EXIT HOUSING



INLET: TOROIDAL, RADIAL
EXIT: AXIAL

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 6 - PUMPHOUSING

- CAST INCO 718

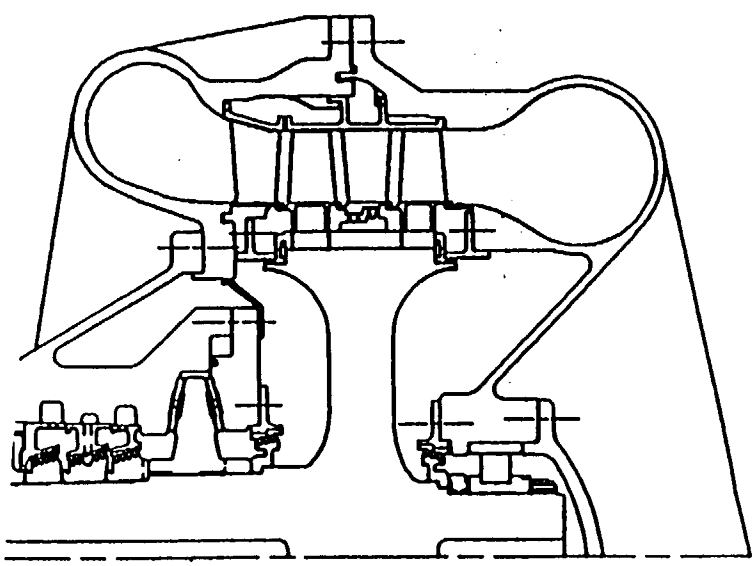
ITEM 7 - INTERPROPELLANT SEAL (IPS)

- LAB SEALS
- CARBON SEALS
- BRUSH SEALS
- TEXAS SEAL

UNITED TECHNOLOGIES PRATT&WHITNEY

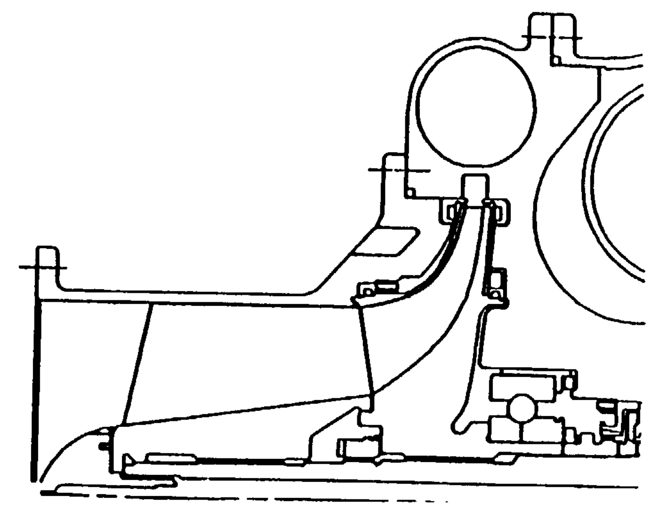
ADP OXYGEN TURBOPUMP TRADE STUDIES

ITEM 1b - THRUST PISTON



SEPERATE THRUST PISTON

- LIMITS BEARING AXIAL LOADS
- REQUIRES ADDITIONAL H_2 FLOW



IMPELLER AS THRUST PISTON

- ELIMINATES THE ADDTIONAL H_2 FLOW
- BALL BEARING MUST TAKE THE AXIAL THRUST LOADS DURING TRANSIENTS

UNITED TECHNOLOGIES PRATT&WHITNEY

ADP OXYGEN TURBOPUMP TRADE STUDIES

SUMMARY

ITEMS ELIMINATED INCLUDE:

- SOLID BLADES
- SINGLE STAGE TURBINE
- UNDAMPED BLADES
- IBR'S
- TWO INDIVIDUAL DISKS

REMIANING OPEN ITEMS TO BE RESOLVED BY JAN -FEB 90

2.1.2 FABRICATION TRADES

IMPELLER

THIS TRADE STUDY INVESTIGATED FOUR POSSIBLE FABRICATION PROCESSES FOR THE IMPELLER. MICROCAST INC0 718 HUB AND SHROUD IS THE BASELINE CONCEPT. FORGED HUB/DIFFUSION BONDED SHROUD, FORGED HUB WITH CAST SHROUD AND POWDER METAL INTEGRAL IMPELLER USING RAPID OMNIDIRECTIONAL COMPACTION (ROC) ARE ALTERNATIVES # 1, 2 AND 3, RESPECTIVELY.

COST ESTIMATES FOR THE BI-CAST AND ROC PROCESS CAN NOT BE PROJECTED AT THIS TIME SINCE THE PROCESSES ARE BEING DEVELOPED. P&W IS INVESTIGATING BOTH PROCESSES FOR FUTURE APPLICATION IN THE LOX TURBOPUMP.

FAILURE MODES CONSIDERED IN THE RELIABILITY ANALYSIS ARE CAVITATION EROSION, CRACKING AND MATERIAL DEFECTS. FROM A SAFETY PERSPECTIVE, THE FORGED HUB HAS BETTER RESISTANCE TO CAVITATION EROSION.

OXIDIZER TURBOPUMP ADVANCED DEVELOPMENT PROGRAM

TRADE STUDY TABLE FOR SELECTION OF IMPELLER FABRICATION.

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION		PUMP LEVEL CONFIGURATION		WEIGHTED RATIO	
		B/L	ALT1	B/L	ALT1	B/L	ALT1
PRODUCTION RELATED ITEMS							
• Production Selling Price($)	31.9	104,754	149,901	1,123,531	1,168,678	0.319	0.332
• Manufacturing Investment Cost($)	3.2	1	1	1	1	0.032	0.032
OPERATION AND SUPPORT ITEMS							
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2	N/A		31	31	0.102	0.102
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0	N/A		N/A		N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	8.5	8.4	435.4	435.3	0.017	0.017
• Logistic Support Cost($)	3.2	1	1	1	1	0.032	0.032
RELIABILITY RELATED ITEMS							
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0075	0.0087	0.157	0.1582	0.391	0.394
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.00102	0.00089	0.0546	0.0545	0.035	0.034
OTHER ITEMS							
• Efficiency	0.0	N/A		N/A		0.000	0.000
• Weight(lbm)	1.8	63.4	63.4	1510	1510	0.018	0.018
• Engine Development Cost($)	5.3	1	1	1	1	0.053	0.053
TOTAL(%)	100.0					100.000	101.504

1.0

NOTE:
B/L--Integrally Cast Hub and Shroud. ALT 1--Forged Hub with Diffusion Bonded Shroud.
See Narrative for: ALT 2-- Forged Hub with Cast Shroud and ALT 3-- Powder Metal (ROC).
N/A--Not Applicable, 1--No Significant Difference.
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

ADP - 13

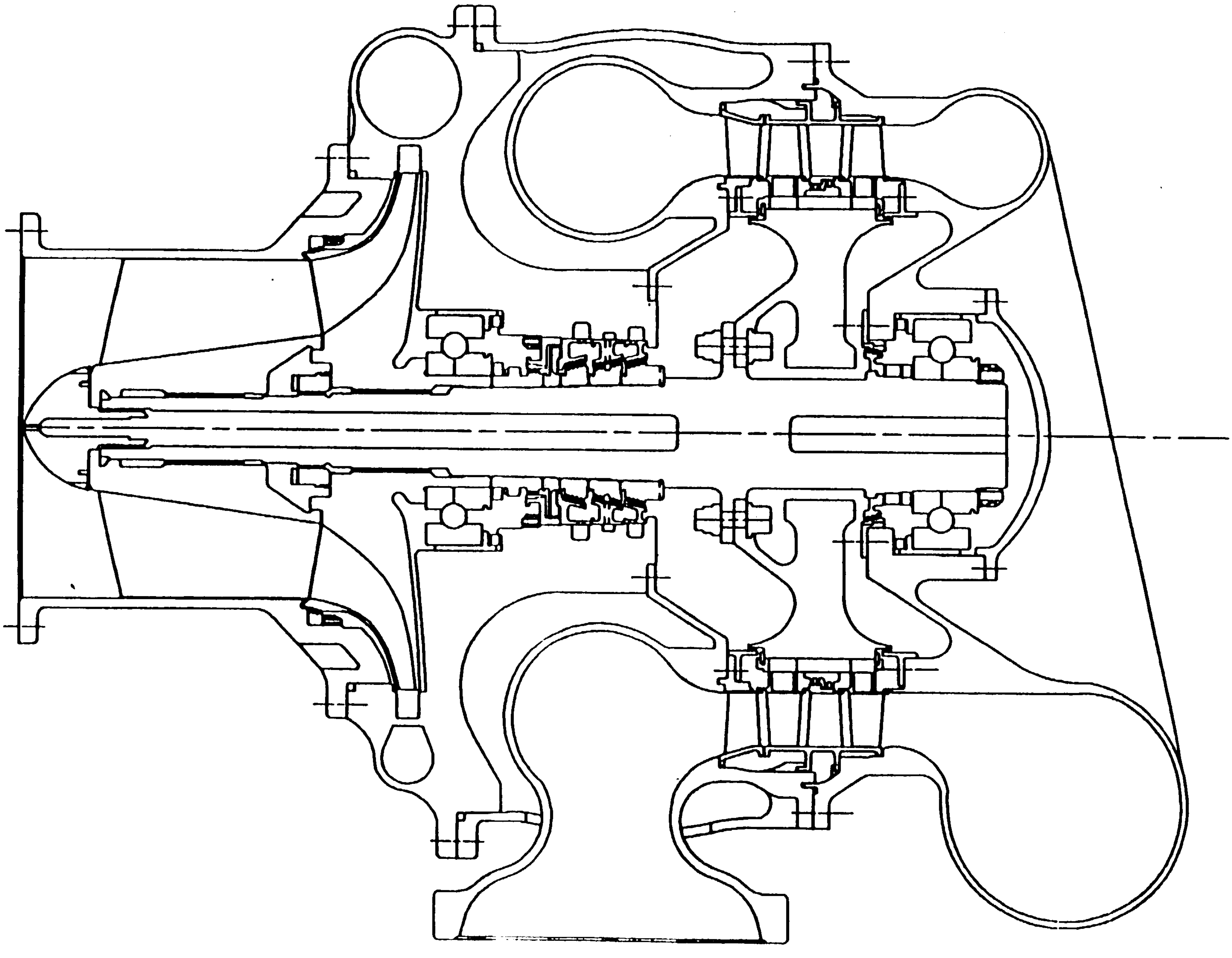


FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR IMPELLER FABRICATION.

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF IMPELLER FABRICATION.

TRADE TABLE INPUTS:

PRODUCTION COST–

MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	29700
•ALT1:	42500

UNSCHEDULED MAINTENANCE COST–

RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.0762
•ALT1:	0.0645

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.3232

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	294.41
•ALT1:	294.41

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:-13	1510
•ALT1:-13	1510

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	63.4
•ALT1:-13	63.4

WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST–

ENGINE LEVEL TFU: Includes markups.

•B/L	10301000

RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS–

Time, entered at the ENGINE LEVELin mmh.

•B/L	118.3

UNSCHEDULED MAINTENANCE COST–

Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.

•B/L	125.8635

PROBABILITY OF VEHICLE LOSS–

Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.

•B/L	1.176

PROBABILITY OF LAUNCH DELAY–

Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.

•B/L	1.543

WEIGHT--GG Weight per TIM 3/90.

Engine level weight, lbs

•B/L	8147

NOTE:

Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table. All inputs are colored red.

TURBINE INLET HOUSING

THIS TRADE STUDY COMPARED A TOROIDAL HOUSING CONFIGURATION TO A VOLUTE HOUSING CONFIGURATION. BASELINE CONFIGURATION IS THE TOROIDAL (dwg ADP-13) WHICH HAS A RADIAL INLET WITH CONSTANT ARLA INLET FLOWPATH. VOLUTE INLET CONFIGURATION (dwg ADP-10) WHICH HAS A CONVERGING CONSTANT AREA MANIFOLD IS ALTERNATE #1. HOUSING MATERIAL IS MICROCAST HAYNES 230.

CASTING VENDOR HAS VERIFIED THAT A RADIAL INLET IS EASIER TO CAST BECAUSE IT HAS A CONSTANT AREA CORE. HOWEVER, IT WOULD BE TWO SEPARATE CASTINGS REQUIRING A CIRCUMFERENTIAL WELD.

THREE FAILURE MODES WERE CONSIDERED IN THIS ANALYSIS: CRACKING/FRACTURE, EROSION AND CONTAMINATION. TOROIDAL INLET HOUSING HAS A HIGHER VEHICLE LOSS RATE AND LAUNCH DELAY RATE THAN THE VOLUTE DUE TO THE WELD AND VARYING PRESSURE DISTRIBUTION.

OXIDIZER TURBOPUMP ADVANCED DEVELOPMENT PROGRAM

TRADE STUDY TABLE FOR SELECTION OF TURBINE INLET HOUSING.

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION		PUMP LEVEL CONFIGURATION		WEIGHTED RATIO	
		B/L	ALT1	B/L	ALT1	B/L	ALT1
PRODUCTION RELATED ITEMS							
• Production Selling Price($)	31.9	186,582	192,931	1,123,531	1,129,880	0.319	0.321
•Manufacturing Investment Cost($)	3.2	1	1	1	1	0.032	0.032
OPERATION AND SUPPORT ITEMS							
•Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2	N/A		31	31	0.102	0.102
•Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0	N/A		N/A		N/A	
•Unscheduled Maintenance Cost ($/Firing)	1.7	12.6	11.9	435.4	434.7	0.017	0.016
•Logistic Support Cost($)	3.2	1	1	1	1	0.032	0.032
RELIABILITY RELATED ITEMS							
•Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0112	0.0076	0.157	0.1534	0.391	0.382
•Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0011	0.001	0.0546	0.0545	0.035	0.034
OTHER ITEMS							
•Efficiency	0.0	N/A		N/A		0.000	0.000
•Weight(lbm)	1.8	308.4	189.7	1510	1391	0.018	0.017
•Engine Development Cost($)	5.3	1	1	1	1	0.053	0.053
TOTAL(%)	100.0					100.000	98.998

NOTE:
B/L--Torodial ALT 1--Volute.
N/A--Not Applicable, 1--No Significant Difference.
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR TURBINE INLET HOUSING.

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF TURBINE INLET HOUSING.

TRADE TABLE INPUTS:

PRODUCTION COST--

MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	52900
•ALT1:	54700

UNSCHEDULED MAINTENANCE COST--

RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.0802
•ALT1:	0.0756

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.3303

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	389.24
•ALT1:	375.2

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:-13	1510
•ALT1:-10	1391.3

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	308.4
•ALT1:-10	189.7

WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST--

ENGINE LEVEL TFU: Includes markups.

•B/L	10301000

RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS--

Time , entered at the ENGINE LEVELin mmh.

•B/L	118.3

UNSCHEDULED MAINTENANCE COST--

Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.

•B/L	125.8635

PROBABILITY OF VEHICLE LOSS--

Vehicle Loss Rate , entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.

•B/L	1.176

PROBABILITY OF LAUNCH DELAY--

Launch Delay Rate , entered at the ENGINE LEVEL in Launch Delays/1000 Firings.

•B/L	1.543

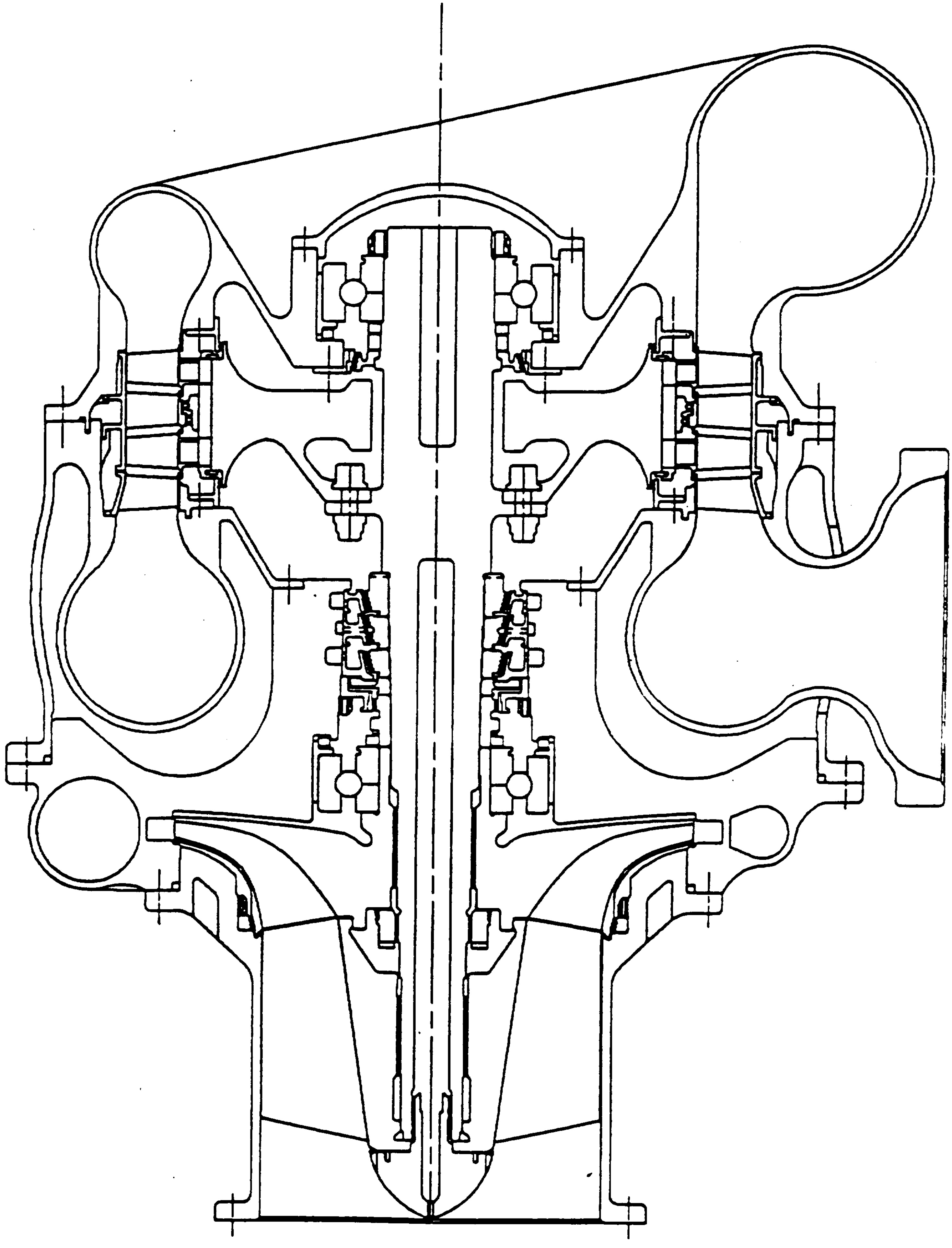
WEIGHT--GG Weight per TIM 3/90.

Engine level weight, lbs

•B/L	8147

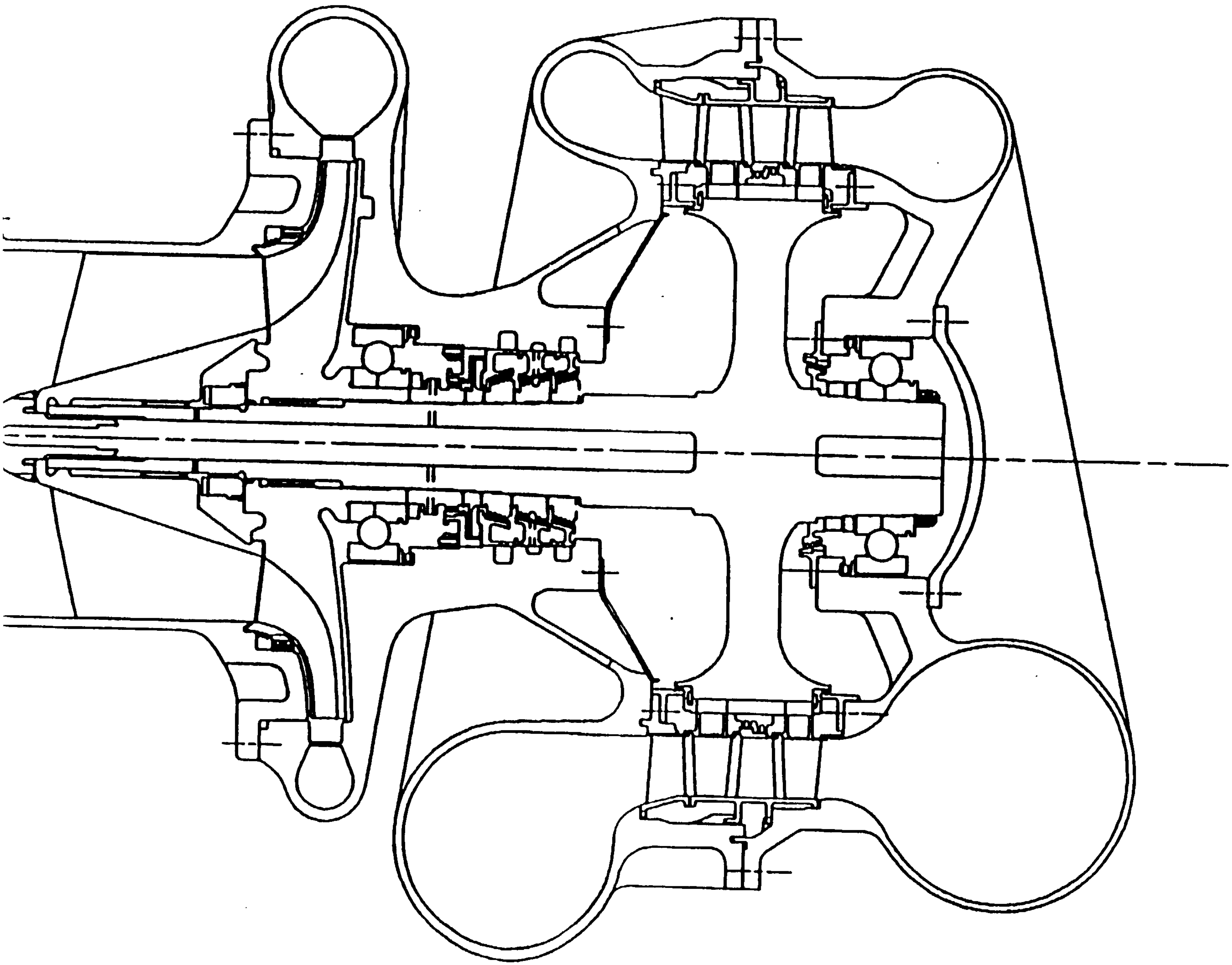
NOTE:

Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.
All inputs are colored red.



· 13

ADP - 10



TURBINE EXIT HOUSING

THIS TRADE STUDY COMPARES A VOLUTE CONFIGURATION TO AN AXIAL EXIT HOUSING. THE VOLUTE EXIT HOUSING (dwg ADP-13) SERVES AS THE BASELINE CONFIGURATION AND ALTERNATE #1 IS THE AXIAL CONFIGURATION (ADP-11). HOUSING MATERIAL IS MICROCAST HAYNES 230 WHICH HAS GOOD RESISTANCE TO HYDROGEN EMBRITTLEMENT.

AERODYNAMICS ANALYSIS INDICATES THE AXIAL FLOW DISCHARGE CONFIGURATION WOULD REQUIRE FOUR EXIT GUIDE VANES (232 TOTAL AIRFOILS) TO STRAIGHTEN THE EXIT SWIRL. THIS IS NEEDED TO AVOID CHOKING DUE TO FLOW VORTEXING.

A VOLUTE CONFIGURATION ALLOWS THE BEARINGS TO BE LOCATED AFT OF THE TURBINE DISK. ALSO, IT PROVIDES A STIFF HOUSING SUPPORT FOR THE BEARINGS, PERMITS EASY ACCESS FOR BEARING INSPECTION AND CONSTANT PRESSURE DISTRIBUTION.

THREE FAILURE MODES WERE CONSIDERED IN THE RELIABILITY ANALYSIS. THEY ARE CRACKING/FRACTURE, EROSION AND CONTAMINATION.

TRADE STUDY TABLE FOR SELECTION OF TURBINE EXIT HOUSING.

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION B/L	PART LEVEL CONFIGURATION ALT1	PUMP LEVEL CONFIGURATION B/L	PUMP LEVEL CONFIGURATION ALT1	WEIGHTED RATIO B/L	WEIGHTED RATIO ALT1
PRODUCTION RELATED ITEMS							
• Production Selling Price($)	31.9	157,308	183,055	1,123,531	1,149,279	0.319	0.327
• Manufacturing Investment Cost($)	3.2	1	1	1	1	0.032	0.032
OPERATION AND SUPPORT ITEMS							
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2	N/A		31	52.6	0.102	0.174
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0	N/A		N/A		N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	11.3	13.3	435.4	437.4	0.017	0.020
• Logistic Support Cost($)	3.2	1	1	1	1	0.032	0.032
RELIABILITY RELATED ITEMS							
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0073	0.0059	0.157	0.1556	0.391	0.388
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0011	0.0012	0.0546	0.0547	0.035	0.035
OTHER ITEMS							
• Efficiency	0.0	N/A		N/A		0.000	0.000
• Weight(lbm)	1.8	253.4	188	1510	1445	0.018	0.017
• Engine Development Cost($)	5.3	1	1	1	1	0.053	0.053
TOTAL(%)	100.0					100.000	107.684

NOTE:
B/L--Volute ALT 1--Axial.
N/A--Not Applicable, 1--No Significant Difference.
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR TURBINE EXIT HOUSING.

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF TURBINE EXIT HOUSING.

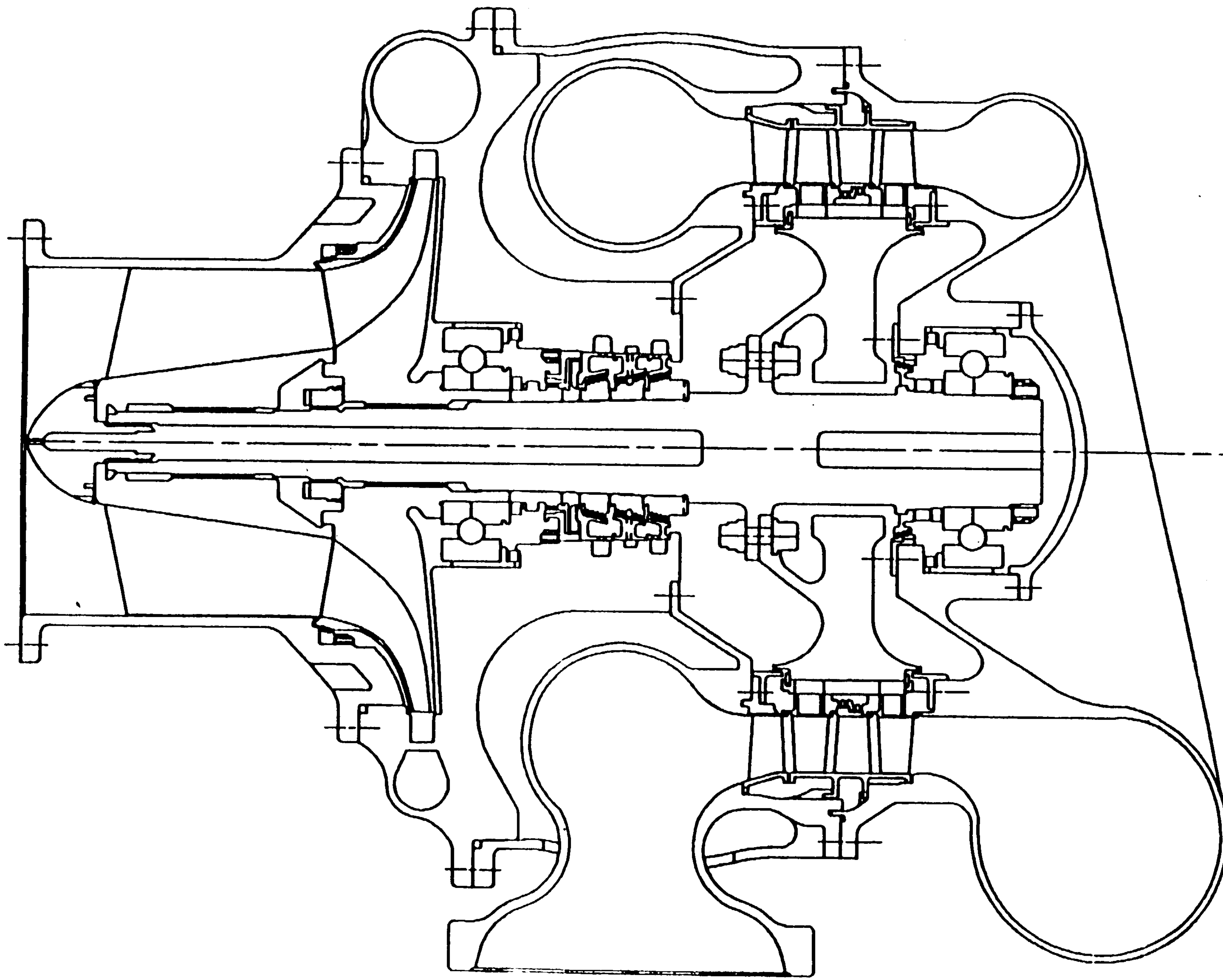
TRADE TABLE INPUTS:

PRODUCTION COST--
MANUFACTURING: MD Costs, entered at the PART LEVEL.
•B/L: 44600
•ALT1: 51900
UNSCHEDULED MAINTENANCE COST--
RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.
•B/L: 0.0841
•ALT1: 0.0919
RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.
•B/L: 4.3349
•ALT1: 4.3427
MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.
•B/L: 311.71
•ALT1: 306.62
WEIGHT: Total Weight at the PUMP LEVEL, lbs.
•B/L:-13 1510
•ALT1:-11 1445
WEIGHT: Total Weight at the PART LEVEL, lbs.
•B/L:-13 253.4
•ALT1:-10 188

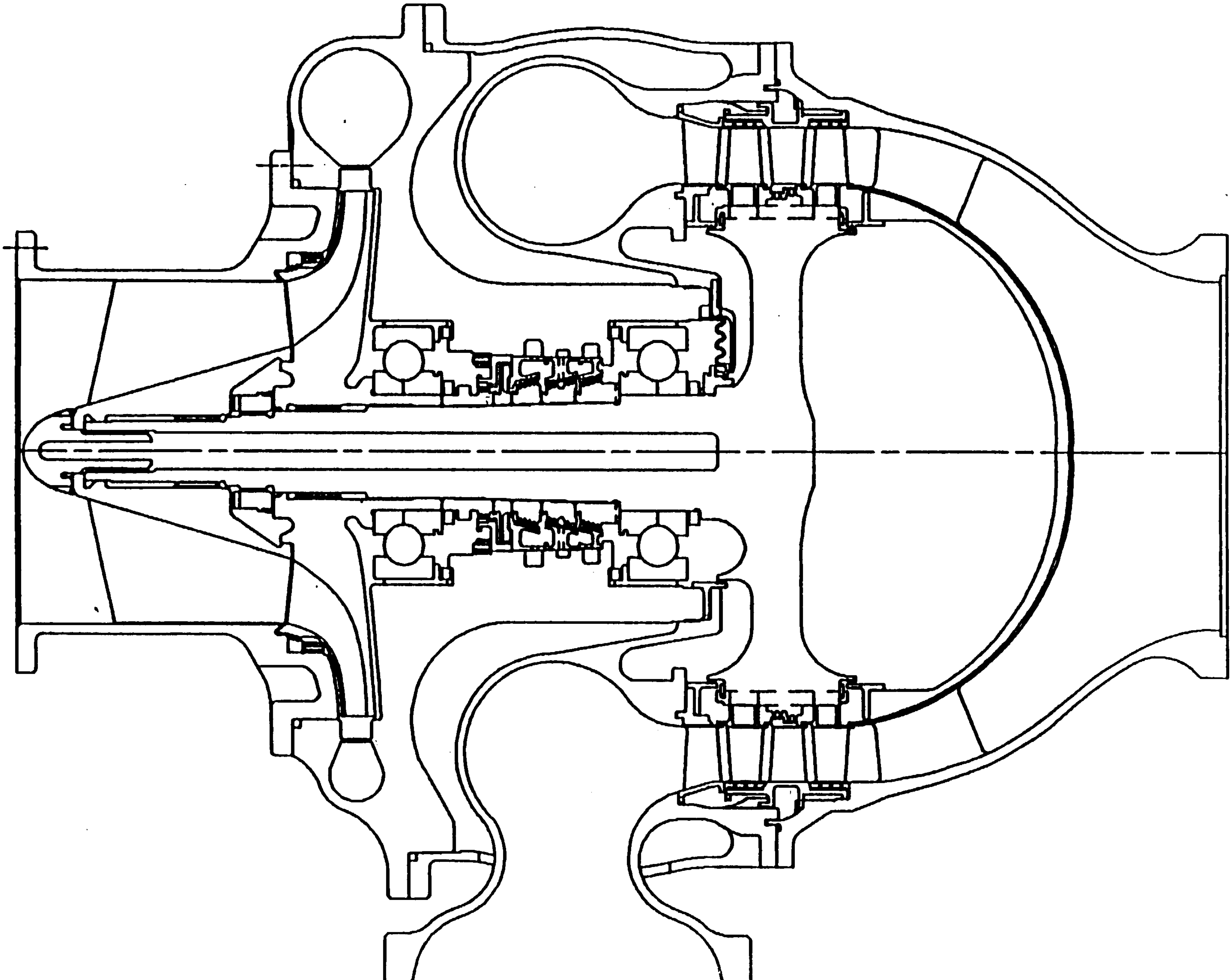
WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST--
ENGINE LEVEL TFU: Includes markups.
•B/L 10301000
RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS--
Time, entered at the ENGINE LEVELin mmh.
•B/L 118.3
UNSCHEDULED MAINTENANCE COST--
Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.
•B/L 125.8635
PROBABILITY OF VEHICLE LOSS--
Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.
•B/L 1.176
PROBABILITY OF LAUNCH DELAY--
Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.
•B/L 1.543
WEIGHT--GG Weight per TIM 3/90.
Engine level weight, lbs
•B/L 8147
NOTE:
Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.
All inputs are colored red.

AL -13



ADP - 11



SHAFT / DISK

THREE CONCEPTS WERE CONSIDERED IN THE TRADE STUDY FOR THE SHAFT / DISK. BOLTED CONFIGURATION (dwg ADP-13) IS THE BASELINE. INERTIA WELDED (dwg ADP-10) AND FORGED ONE PIECE (dwg ADP-10) ARE ALTERNATIVES # 1 AND 2, RESPECTIVELY. SHAFT / DISK MATERIAL IS A286 FOR ALL OPTIONS, WHICH HAS GOOD RESISTANCE TO HYDROGEN EMBRITTLEMENT. BOLTED SHAFT AND DISK ALLOWS USE OF DISSIMILAR MATERIAL.

INERTIA WELD TRIALS AND A ONE PIECE FORGING DEMO ARE BEING CONDUCTED TO DEFINE THE PROCESS PARAMETERS.

FAILURE MODES CONSIDERED IN THE RELIABILITY ANALYSIS ARE: DISK CRACKING, OVERTEMPS, SHAFT FRACTURE / DISTORTION AND BOLT FRACTURE.

TRADE STUDY FOR SELECTION OF SHAFT AND DISK.

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION			PUMP LEVEL CONFIGURATION			WEIGHTED RATIO		
		B/L	ALT1	ALT2	B/L	ALT1	ALT2	B/L	ALT1	ALT2
PRODUCTION RELATED ITEMS										
• Production Selling Price($)	31.9	158,366	175,296	134,029	1,123,531	1,140,461	1,099,194	0.319	0.324	0.313
• Manufacturing Investment Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
OPERATION AND SUPPORT ITEMS										
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2		N/A		31	31	31	0.102	0.102	0.102
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0		N/A			N/A			N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	10.3	9.0	7.4	435.4	434.2	432.5	0.017	0.015	0.012
• Logistic Support Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
RELIABILITY RELATED ITEMS										
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0012	0.0016	0.0014	0.157	0.1574	0.1572	0.391	0.392	0.392
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0009	0.0008	0.0007	0.0546	0.0545	0.0544	0.035	0.034	0.034
OTHER ITEMS										
• Efficiency	0.0		N/A			N/A		0.000	0.000	0.000
• Weight(lbm)	1.8	176	150.2	150.2	1510	1484	1484	0.018	0.018	0.018
• Engine Development Cost($)	5.3	1	1	1	1	1	1	0.053	0.053	0.053
TOTAL(%)	100.0							100.000	100.287	98.795

NOTE:
B/L–Bolted Shaft/Disk, ALT1–Inertia Welded Shaft/Disk, ALT2–One-Piece Forged Shaft/Disk
N/A–Not Applicable, 1--No Significant Difference.
Maintenance– occurs after the launch, Launch Delay –at the pad, Analysis--at the pump level

FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR SHAFT AND DISK .

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF SHAFT AND DISK

TRADE TABLE INPUTS:

PRODUCTION COST–

MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	44900
•ALT1:	49700
•ALT2:	38000

UNSCHEDULED MAINTENANCE COST–

RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.072
•ALT1:	0.0606
•ALT2:	0.0561

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.3235
•ALT2:	4.319

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	373.5
•ALT1:	366.2
•ALT2:	366.2

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:	1510
•ALT1:	1484
•ALT2:	1484

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	176
•ALT1:-10	150.2
•ALT2:-10	150.2

WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST–

ENGINE LEVEL TFU: Includes markups.

•B/L	10301000

RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS–

Time, entered at the ENGINE LEVELin mmh.

•B/L	118.3

UNSCHEDULED MAINTENANCE COST–

Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.

•B/L	125.8635

PROBABILITY OF VEHICLE LOSS–

Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.

•B/L	1.176

PROBABILITY OF LAUNCH DELAY–

Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.

WEIGHT–GG Weight per TIM 3/90.

Engine level weight, lbs

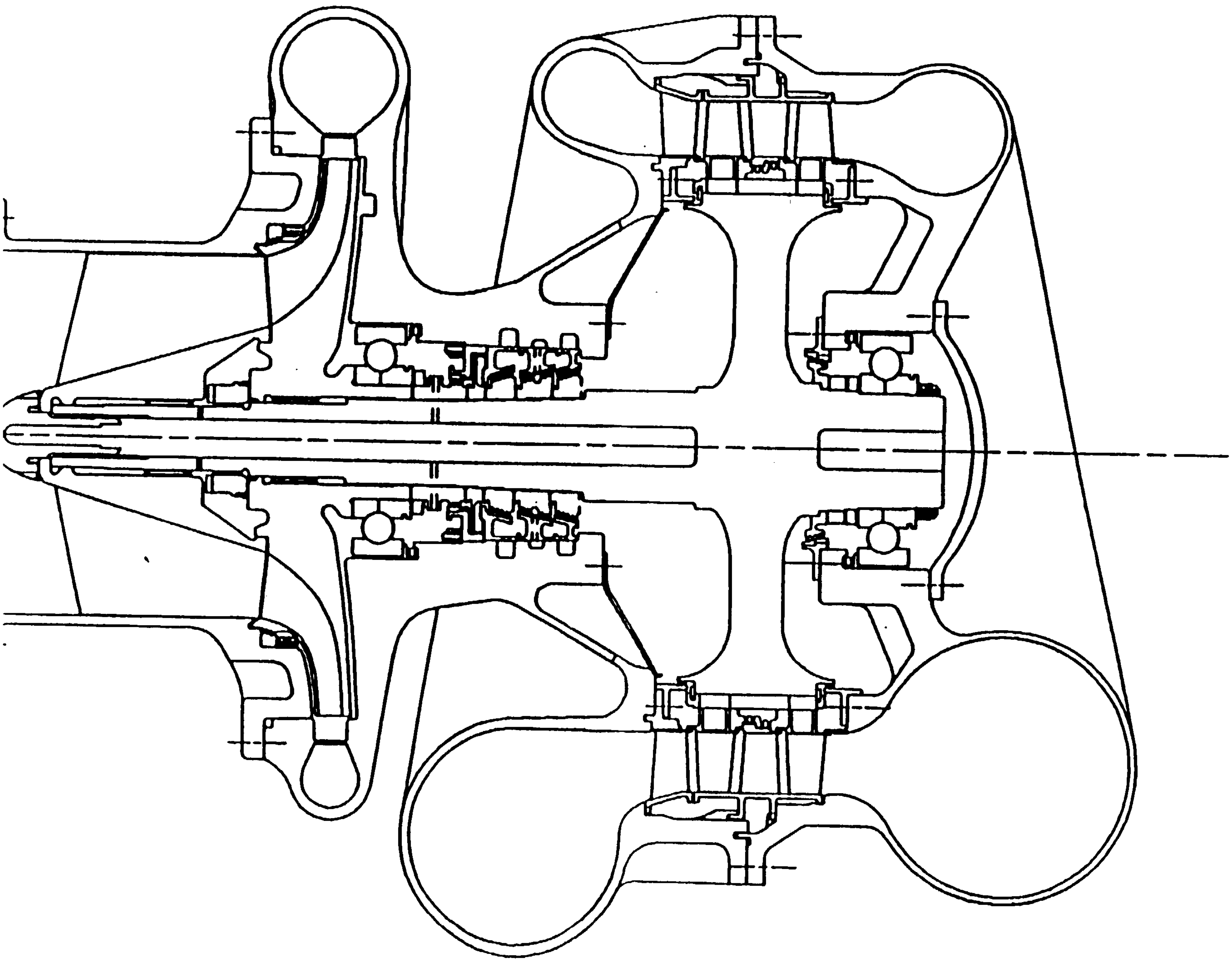
•B/L	8147

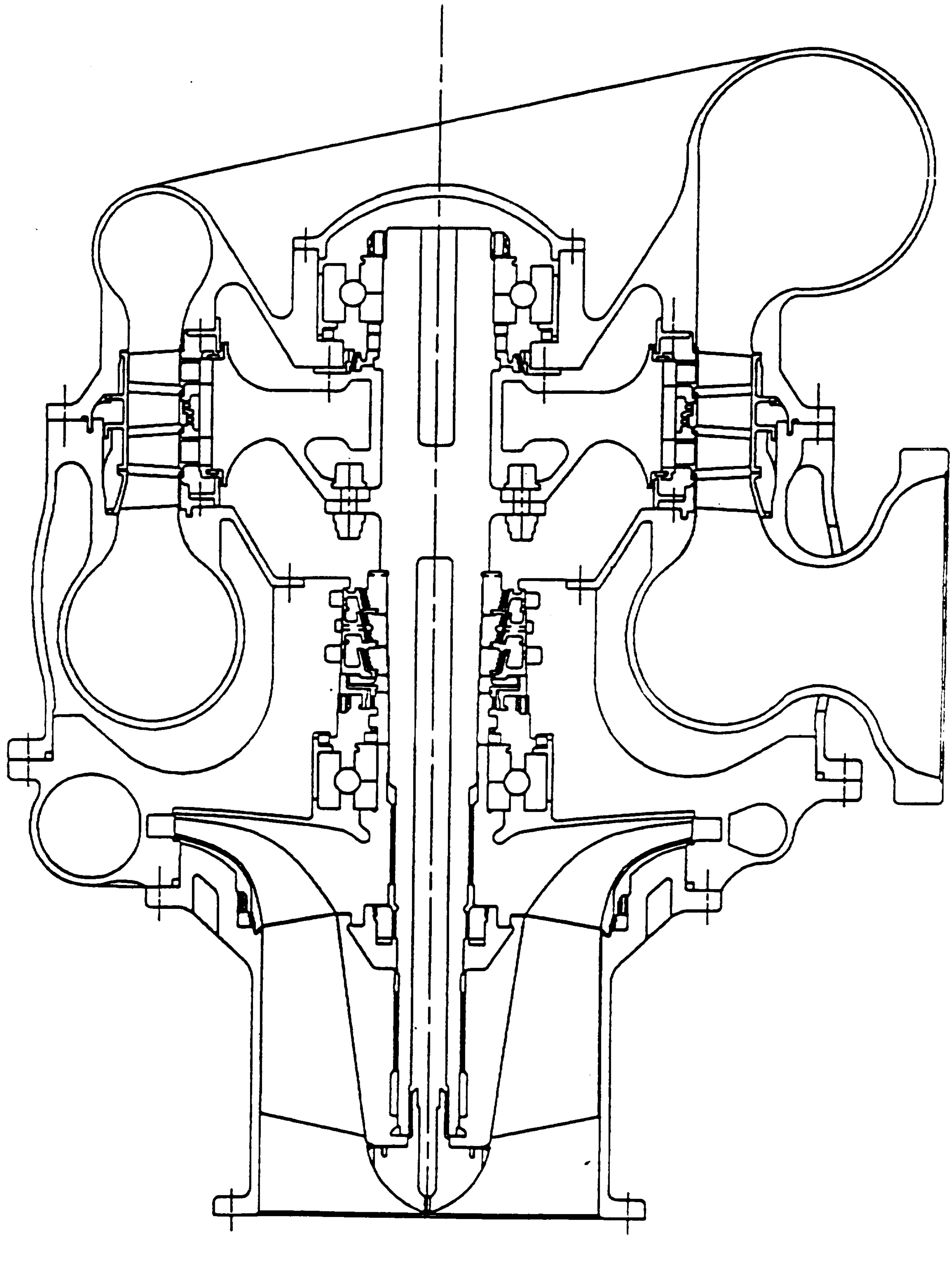
NOTE:

Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.

All inputs are colored red.

ADP - 10





AL 13

BEARINGS

THIS TRADE EVALUATES THREE CONFIGURATIONS, FOCUSING ON THE BEARING TYPE AND LOCATION. A BALL / BALL COMBINATION WITH A STRADDLED MOUNTED TURBINE ROTOR (dwg ADP-13) IS THE BASELINE. ALTERNATIVES #1 AND 2 ARE BALL / ROLLER WITH STRADDLE MOUNTED TURBINE (dwg ADP-6) AND BALL / BALL WITH OVERHUNG TURBINE ROTOR (dwg ADP-11). BALL BEARINGS ARE DERIVATIVE ATD BALL BEARINGS WITH A LARGER DIAMETER TO FIT THE ROTOR SHAFT OUTER DIAMETER.

STRADDLED TURBINE CONCEPT IMPROVES THE CRITICAL SPEED AND HAS A STIFFER HOUSING SUPPORT. THE INCREASED SPRING RATE OBTAINED FROM A ROLLER BEARING IS NOT NECESSARY FOR THE LOX TURBOPUMP. ALSO, A BEARING LOCATED AFT OF THE TURBINE DISK ALLOWS EASIER ACCESS FOR INSPECTION AND MAINTENANCE.

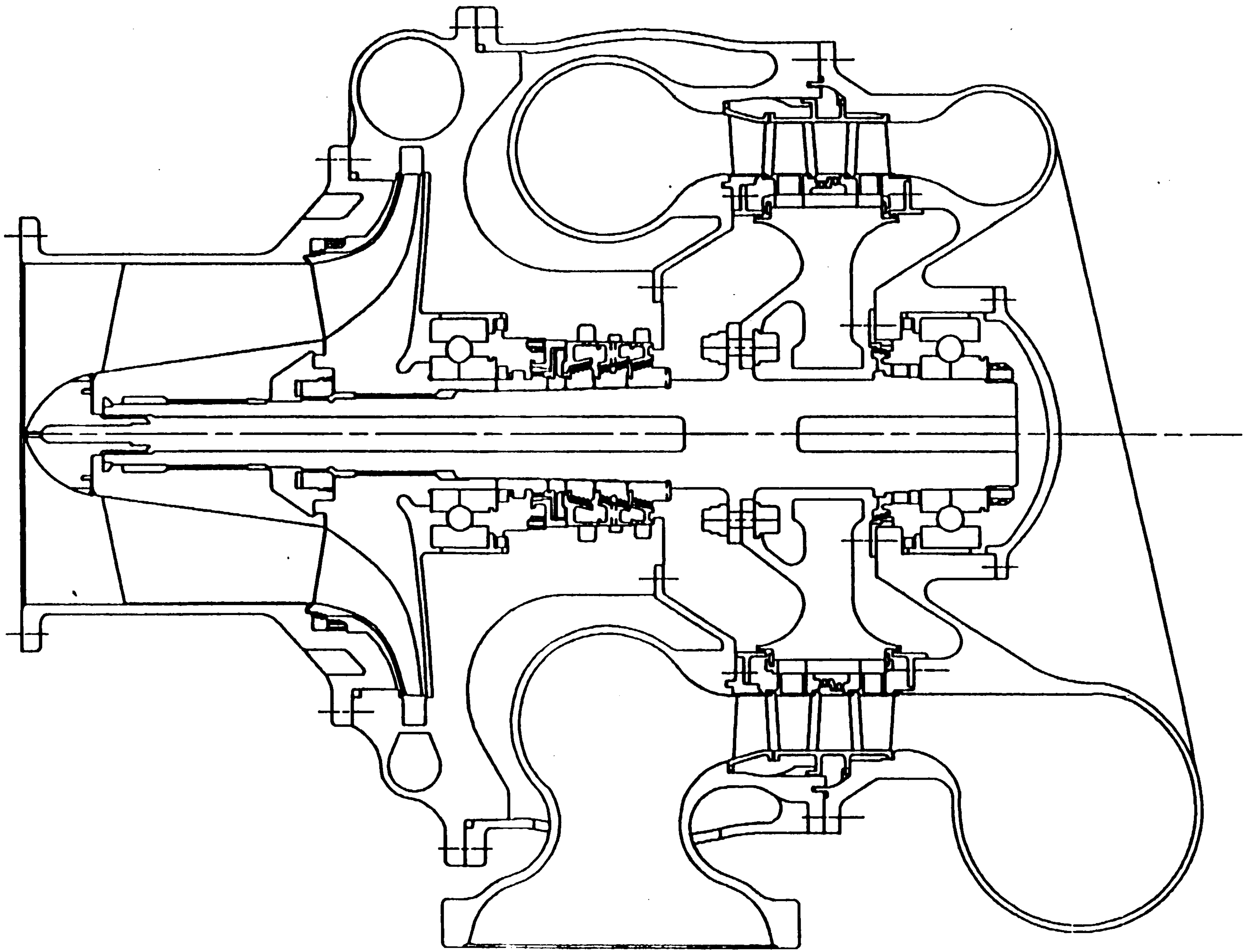
FOUR MAIN FAILURE MODES WERE CONSIDERED IN THE RELIABILITY ANALYSIS: WEAR, SPALLING, CRACKING AND CONTAMINATION.

TRADE STUDY TABLE FOR SELECTION OF BEARINGS

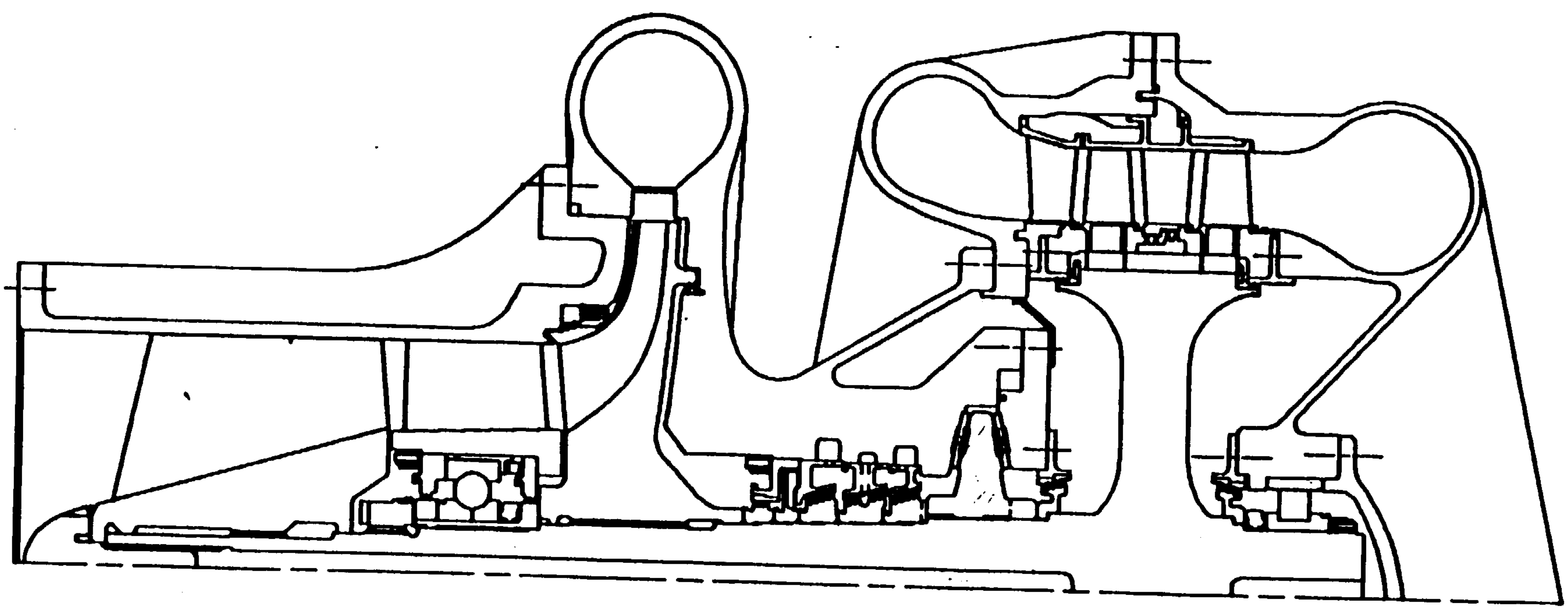
EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION			PUMP LEVEL CONFIGURATION			WEIGHTED RATIO		
		B/L	ALT1	ALT2	B/L	ALT1	ALT2	B/L	ALT1	ALT2
PRODUCTION RELATED ITEMS										
• Production Selling Price($)	31.9	23,984	19,752	23,984	1,123,531	1,119,299	1,123,531	0.319	0.318	0.319
• Manufacturing Investment Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
OPERATION AND SUPPORT ITEMS										
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2		N/A		31	31	52.61	0.102	0.102	0.174
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0		N/A			N/A			N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	31	18	43	435.4	422.4	447.8	0.017	0.010	0.024
• Logistic Support Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
RELIABILITY RELATED ITEMS										
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.009	0.0065	0.0125	0.157	0.1545	0.1605	0.391	0.385	0.400
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0101	0.0083	0.0111	0.0546	0.0528	0.0556	0.035	0.033	0.035
OTHER ITEMS										
• Efficiency	0.0		N/A			N/A		0.000	0.000	0.000
• Weight(lbm)	1.8	27.7	9.3	32.6	1510	1492	1515	0.018	0.018	0.018
• Engine Development Cost($)	5.3	1	1	1	1	1	1	0.053	0.053	0.053
TOTAL(%) :	100.0							100.000	98.362	108.702

NOTE:
B/L–New Ball/Ball with Straddled Turbine, ALT1--New Ball/ATD Roller with Straddled Turbine, ALT2–New Ball/Ball with Overhung Turbine
N/A–Not Applicable, 1–No significant difference.
Maintenance– occurs after the launch, Launch Delay --at the pad, Analysis–at the pump level

AD 13



ADP - 6



ADP - 11

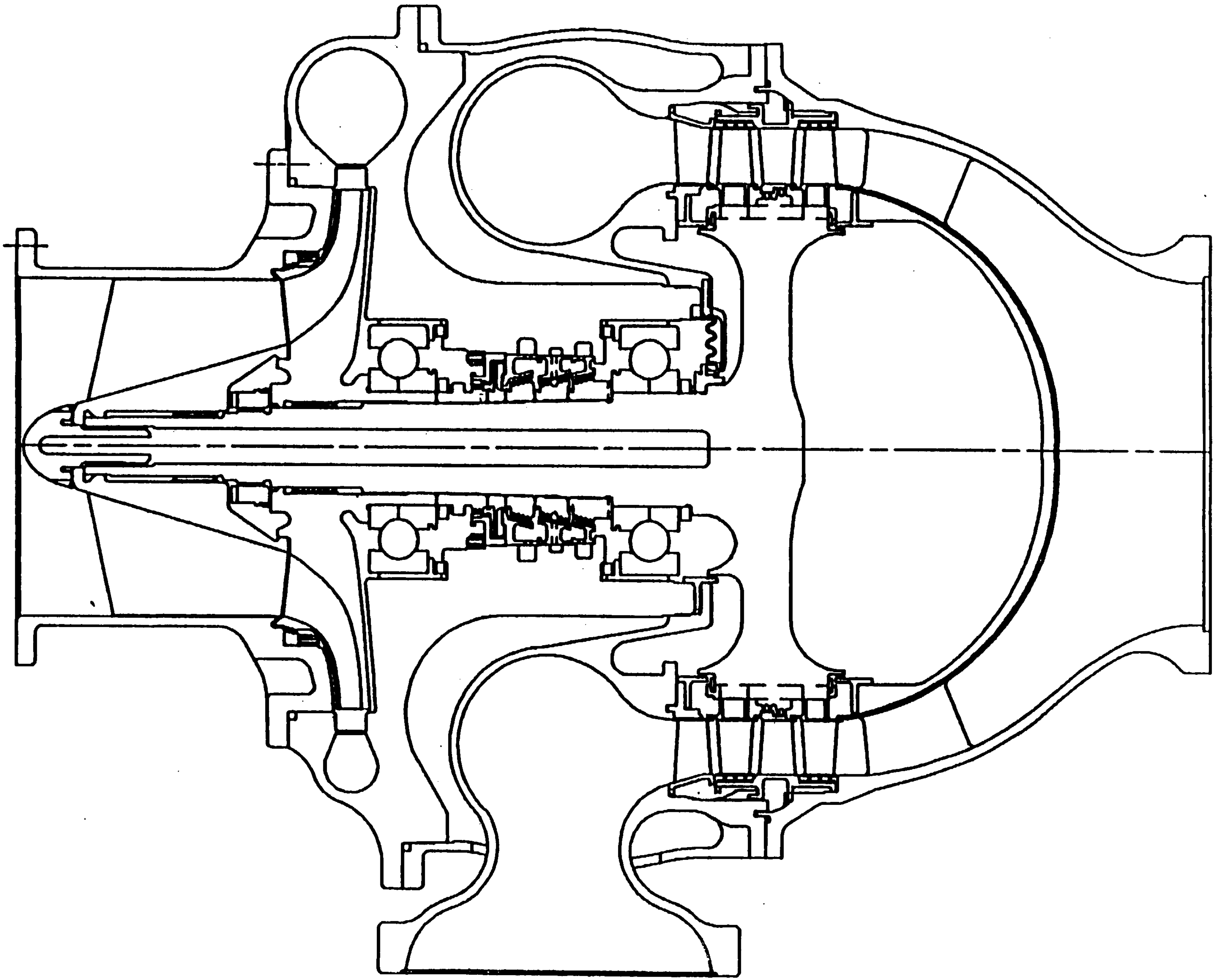


FIGURE 1 - TRADE STUDY TABLE FOR SELECTION OF BEARINGS

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION			PUMP LEVEL CONFIGURATION			WEIGHTED RATIO		
		B/L	ALT1	ALT2	B/L	ALT1	ALT2	B/L	ALT1	ALT2
PRODUCTION RELATED ITEMS										
• Production Selling Price($)	31.9	21,586	19,752	21,586	1,123,531	1,121,697	1,123,531	0.319	0.319	0.319
• Manufacturing Investment Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
OPERATION AND SUPPORT ITEMS										
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2		N/A		31	31	52.61	0.102	0.102	0.174
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0		N/A			N/A			N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	30	18	42	435.4	423.2	447.6	0.017	0.010	0.024
• Logistic Support Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
RELIABILITY RELATED ITEMS										
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.009	0.0065	0.0125	0.157	0.1545	0.1605	0.391	0.385	0.400
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0101	0.0083	0.0111	0.0546	0.0528	0.0556	0.035	0.033	0.035
OTHER ITEMS										
• Efficiency	0.0		N/A			N/A		0.000	0.000	0.000
• Weight(lbm)	1.8	27.7	9.3	32.6	1510	1492	1515	0.018	0.018	0.018
• Engine Development Cost($)	5.3	1	2	1	1	1.05	1	0.053	0.056	0.053
TOTAL(%)	100.0							100.000	98.719	108.710

NOTE:
B/L–New Ball/Ball with Straddled Turbine, ALT1–New Ball/ATD Roller with Straddled Turbine, ALT2–New Ball/Ball with Overhung Turbine
N/A–Not Applicable, 1–No significant difference.
Maintenance– occurs after the launch, Launch Delay –at the pad, Analysis–at the pump level
Production Parts Cost Adjusted for Like Parts.

FIGURE2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR BEARINGS.

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3- TRADE STUDY INPUTS FOR SELECTION OF BEARINGS.

TRADE TABLE INPUTS:

PRODUCTION COST–

MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	6800
•ALT1:	5600
•ALT2:	6800

UNSCHEDULED MAINTENANCE COST--

RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.3843
•ALT1:	0.2319
•ALT2:	0.4581

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.1825
•ALT2:	4.4087

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	306.6
•ALT1:	293.27
•ALT2:	414.68

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:-13	1510
•ALT1:-6	1491.6
•ALT2:-11	1514.9

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	27.7
•ALT1:-6	9.3
•ALT2:-11	32.6

WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST–

ENGINE LEVEL TFU: Includes markups.

•B/L 10301000

RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS–

Time, entered at the ENGINE LEVEL in mmh.

•B/L 118.3

UNSCHEDULED MAINTENANCE COST–

Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.

•B/L 125.8635

PROBABILITY OF VEHICLE LOSS–

Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.

•B/L 1.176

PROBABILITY OF LAUNCH DELAY–

Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.

•B/L 1.543

WEIGHT--GG Weight per TIM 3/90.

Engine level weight, lbs

•B/L 8147

NOTE:

Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.
All inputs are colored red.

OXIDIZER TURBOPUMP ADVANCED DEVELOPMENT PROGRAM

FIGURE 1 - TRADE STUDY TABLE FOR SELECTION OF BEARINGS

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION			PUMP LEVEL CONFIGURATION			WEIGHTED RATIO		
		B/L	ALT1	ALT2	B/L	ALT1	ALT2	B/L	ALT1	ALT2
PRODUCTION RELATED ITEMS										
• Production Selling Price($)	31.9	~~11,992~~	8,465	11,287	1,123,531	~~1,120,004~~	~~1,122,826~~	0.319	0.318	0.319
• Manufacturing Investment Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
OPERATION AND SUPPORT ITEMS										
• Recovery/Refurbishment Operations Labor Requirements(mmh)	10.2		N/A		31	31	52.61	0.102	0.102	0.174
Recovery Routine/Periodic Tasks										
Refurbishment Routine/Periodic Tasks										
• Launch Operations Labor Requirements(mmh)	0.0		N/A			N/A			N/A	
Vehicle Build-up Requirements										
Prelaunch Requirements										
• Unscheduled Maintenance Cost ($/Firing)	1.7	29	17	42	333	311	405	0.017	0.016	0.021
• Logistic Support Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
RELIABILITY RELATED ITEMS										
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.009	0.0065	0.0125	0.157	0.1545	0.1605	0.391	0.385	0.400
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0101	0.0083	0.0111	0.0546	0.0528	0.0556	0.035	0.033	0.035
OTHER ITEMS										
• Efficiency	0.0		N/A			N/A		0.000	0.000	0.000
• Weight(lbm)	1.8	13.7	4.2	16.3	1510	1409	1430	0.018	0.017	0.017
• Engine Development Cost($)	5.3	1	1	1	1	1	1	0.053	0.053	0.053
TOTAL(%)	100.0							100.000	98.882	108.275

NOTE:
B/L--New Ball/Ball with Straddled Turbine, ALT1--New Ball/ATD Roller with Straddled Turbine, ALT2--New Ball/Ball with Overhung Turbine
N/A--Not Applicable, 1--No data available at this time
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

FIGURE2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR BEARINGS.

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.937
• Manufacturing Investment Cost($)	3	10.9	0.327	3.194
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.231
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.5	0.176	1.720
• Logistic Support Cost($)	3	10.9	0.327	3.194
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.091
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.454
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.809
• Engine Development Cost($)	5	10.9	0.545	5.323
TOTAL(%)	100		10.246	100.000

SCALING FACTOR = 9.76034275

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3- TRADE STUDY INPUTS FOR SELECTION OF BEARINGS.

TRADE TABLE INPUTS:
PRODUCTION COST--
MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	3400
•ALT1:	2400
•ALT2:	3200

UNSCHEDULED MAINTENANCE COST--
RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.3925
•ALT1:	0.2381
•ALT2:	0.4695

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.435
•ALT1:	4.3291
•ALT2:	4.5605

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	306.6
•ALT1:	293.27
•ALT2:	414.68

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:-13	1510
•ALT1:-6	1409
•ALT2:-11	1430

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	13.7
•ALT1:-6	4.2
•ALT2:-11	16.3

WEIGHTING FACTOR ADJUSTMENT INPUTS:
PRODUCTION COST--
ENGINE LEVEL TFU: Includes markups.
•B/L 10301000
RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS--
Time, entered at the ENGINE LEVEL in mmh.
•B/L 118.3
UNSCHEDULED MAINTENANCE COST--
Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.
•B/L 125.8635
PROBABILITY OF VEHICLE LOSS--
Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.
•B/L 1.176
PROBABILITY OF LAUNCH DELAY--
Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.
•B/L 1.543
WEIGHT--GG Weight per TIM 3/90.
Engine level weight, lbs
•B/L 8147
NOTE:
Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.
All inputs are colored red.

FIGURE 1 - TRADE STUDY TABLE FOR SELECTION OF TURBINE INLET HOUSING.

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION B/L	PART LEVEL CONFIGURATION ALT1	PUMP LEVEL CONFIGURATION B/L	PUMP LEVEL CONFIGURATION ALT1	WEIGHTED RATIO B/L	WEIGHTED RATIO ALT1
PRODUCTION RELATED ITEMS							
• Production Selling Price($)	31.9	186,582	236,667	1,123,531	1,173,616	0.319	0.334
• Manufacturing Investment Cost($)	3.2	1	1	1	1	0.032	0.032
OPERATION AND SUPPORT ITEMS							
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2	N/A		31	31	0.102	0.102
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	0.0	N/A		N/A		N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	13	13.[illegible]	680	759	0.017	0.019
• Logistic Support Cost($)	3.2	1	1	1	1	0.032	0.032
RELIABILITY RELATED ITEMS							
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0112	0.0076	0.157	0.1534	0.391	0.382
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0011	0.001	0.0546	0.0545	0.035	0.034
OTHER ITEMS							
• Efficiency	0.0	N/A		N/A		0.000	0.000
• Weight(lbm)	1.8	308.4	189.7	1510	1186.4	0.018	0.014
• Engine Development Cost($)	5.3	1	1	1	1	0.053	0.053
TOTAL(%)	100.0					100.000	100.281

NOTE:
B/L--Torodial ALT 1--Volute.
N/A--Not Applicable, 1--No data available at this time
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR TURBINE INLET HOUSING

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF TURBINE INLET HOUSING.

TRADE TABLE INPUTS:

PRODUCTION COST--

MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	52900
•ALT1:	67100

UNSCHEDULED MAINTENANCE COST--

RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.0802
•ALT1:	0.0756

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.3303

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	389.24
•ALT1:	375.2

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:-13	1510
•ALT1:-10	1186.4

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	308.4
•ALT1:-10	189.7

WEIGHTING FACTOR ADJUSTMENT INPUTS:

PRODUCTION COST--

ENGINE LEVEL TFU: Includes markups.

•B/L	10301000

RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS--

Time, entered at the ENGINE LEVELin mmh.

•B/L	118.3

UNSCHEDULED MAINTENANCE COST--

Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.

•B/L	125.8635

PROBABILITY OF VEHICLE LOSS--

Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.

•B/L	1.176

PROBABILITY OF LAUNCH DELAY--

Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.

•B/L	1.543

WEIGHT--GG Weight per TIM 3/90.

Engine level weight, lbs

•B/L	8147

NOTE:

Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.

All inputs are colored red.

FIGURE 1 - TRADE STUDY FOR SELECTION OF SHAFT AND DISK

EVALUATION CRITERIA	WEIGHTING FACTOR WF(%)	PART LEVEL CONFIGURATION B/L	PART LEVEL CONFIGURATION ALT1	PART LEVEL CONFIGURATION ALT2	PUMP LEVEL CONFIGURATION B/L	PUMP LEVEL CONFIGURATION ALT1	PUMP LEVEL CONFIGURATION ALT2	WEIGHTED RATIO B/L	WEIGHTED RATIO ALT1	WEIGHTED RATIO ALT2
PRODUCTION RELATED ITEMS										
• Production Selling Price($)	31.9	158,366	175,296	134,029	1,123,531	1,140,461	1,099,194	0.319	0.324	0.313
• Manufacturing Investment Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
OPERATION AND SUPPORT ITEMS										
• Recovery/Refurbishment Operations Labor Requirements(mmh): Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	10.2		N/A		31	31	31	0.102	0.102	0.102
• Launch Operations Labor Requirements(mmh): Vehicle Build-up Requirements Prelaunch Requirements	0.0		N/A			N/A			N/A	
• Unscheduled Maintenance Cost ($/Firing)	1.7	10	9	7	621	645	572	0.017	0.017	0.015
• Logistic Support Cost($)	3.2	1	1	1	1	1	1	0.032	0.032	0.032
RELIABILITY RELATED ITEMS										
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	39.1	0.0012	0.0016	0.0014	0.157	0.1574	0.1572	0.391	0.392	0.392
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	3.5	0.0009	0.0008	0.0007	0.0546	0.0545	0.0544	0.035	0.034	0.034
OTHER ITEMS										
• Efficiency	0.0		N/A			N/A		0.000	0.000	0.000
• Weight(lbm)	1.8	176	150.2	150.2	1510	1186.4	1186.4	0.018	0.014	0.014
• Engine Development Cost($)	5.3	1	1	1	1	1	1	0.053	0.053	0.053
TOTAL(%)	100.0							100.000	100.203	98.775

NOTE:
B/L--Bolted Shaft/Disk, ALT1--Inertia Welded Shaft/Disk, ALT2--One-Piece Forged Shaft/Disk
N/A--Not Applicable , 1--No data available at this time
Maintenance-- occurs after the launch, Launch Delay --at the pad, Analysis--at the pump level

FIGURE 2 - WEIGHTING FACTOR ADJUSTMENT TABLE FOR SHAFT AND DISK

EVALUATION CRITERIA	ENGINE LEVEL WEIGHTING FACTOR(%)	PUMP/ENGINE (SEE NOTE) (%)	PUMP LEVEL WEIGHTING FACTOR(%)	SCALED PUMP LEVEL WEIGHTING FACTOR(%)
PRODUCTION RELATED ITEMS				
• Production Selling Price($)	30	10.9	3.272	31.949
• Manufacturing Investment Cost($)	3	10.9	0.327	3.195
OPERATION AND SUPPORT ITEMS				
• Recovery/Refurbishment Operations Labor Requirements(mmh) Recovery Routine/Periodic Tasks Refurbishment Routine/Periodic Tasks	4	26.2	1.048	10.235
• Launch Operations Labor Requirements(mmh) Vehicle Build-up Requirements Prelaunch Requirements	4	0.0	0.000	0.000
• Unscheduled Maintenance Cost ($/Firing)	5	3.4	0.172	1.681
• Logistic Support Cost($)	3	10.9	0.327	3.195
RELIABILITY RELATED ITEMS				
• Probability of Vehicle Loss (Vehicle Loss Rate/1000 Firing)	30	13.4	4.005	39.106
• Probability of Launch Delay (Launch Delay Rate/1000 Firing)	10	3.5	0.354	3.455
OTHER ITEMS				
• Efficiency	5	0.1	0.005	0.049
• Weight(lbm)	1	18.5	0.185	1.810
• Engine Development Cost($)	5	10.9	0.545	5.325
TOTAL(%)	100		10.242	100.000

SCALING FACTOR = 9.764132434

NOTE:
Pump/Engine is the percentage of the pump level item relative to the engine level item.

FIGURE 3 - TRADE STUDY INPUTS FOR SELECTION OF SHAFT AND DISK

TRADE TABLE INPUTS:
PRODUCTION COST--
MANUFACTURING: MD Costs, entered at the PART LEVEL.

•B/L:	44900
•ALT1:	49700
•ALT2:	38000

UNSCHEDULED MAINTENANCE COST--
RELIABILITY: Maintenance Rate, entered at the PART LEVEL in Maint. Actions/1000 firings.

•B/L:	0.072
•ALT1:	0.0606
•ALT2:	0.0561

RELIABILITY: Maintenance Rate, entered at the PUMP LEVEL in Maint. Actions/1000 firings.

•B/L:	4.3349
•ALT1:	4.3236
•ALT2:	4.319

MAINTAINABILITY: Total Labor, entered at the PUMP LEVEL in mmh.

•B/L:	373.5
•ALT1:	366.2
•ALT2:	366.2

WEIGHT: Total Weight at the PUMP LEVEL, lbs.

•B/L:	1510
•ALT1:	1186.4
•ALT2:	1186.4

WEIGHT: Total Weight at the PART LEVEL, lbs.

•B/L:-13	176
•ALT1:-10	150.2
•ALT2:-10	150.2

WEIGHTING FACTOR ADJUSTMENT INPUTS:
PRODUCTION COST--
ENGINE LEVEL TFU: Includes markups.
•B/L 10301000
RECOVERY/REFURBISHMENT OPERATIONS LABOR REQUIREMENTS--
Time, entered at the ENGINE LEVEL in mmh.
•B/L 118.3
UNSCHEDULED MAINTENANCE COST--
Maintenance Rate, entered at the ENGINE LEVEL in Maint. Actions/1000 firings.
•B/L 125.8635
PROBABILITY OF VEHICLE LOSS--
Vehicle Loss Rate, entered at the ENGINE LEVEL in Vehicle Losses/1000 Firings.
•B/L 1.176
PROBABILITY OF LAUNCH DELAY--
Launch Delay Rate, entered at the ENGINE LEVEL in Launch Delays/1000 Firings.
•B/L 1.543
WEIGHT--GG Weight per TIM 3/90.
Engine level weight, lbs
•B/L 8147
NOTE:
Only inputs required for calculations are entered in this section. All other inputs are entered in the Trade Study Table.
All inputs are colored red.

2.2 PRELIMINARY DESIGN

A preliminary design of the oxygen turbopump, incorporating low cost, high reliability features, was completed and a Preliminary Design Review (PDR) was conducted at NASA-MSFC on October 24, 1990.

The design reliability improvements included an axial pump inlet, a splitter to reduce pump side loads, a thrust balance system integral with the impeller, low tip speeds, volutes to reduce turbine side loads and flow disturbances, subsonic, hollow, damped, shrouded airfoils, sub critical rotor dynamics, damper seals, a simple forged integral disk and shaft, cast housings with no welds and an optimized flow path.

At PDR the design included low cost improvements developed through integration of engineering, manufacturing suppliers and the customer during the design. Included were a cast inducer, a cast shrouded impeller, interpropellant lab seals with carbon ring buffers, ball bearings at each end, a single disk/shaft, incorporation of low cost materials such as Equiax IN-100 in the turbine blades, Equiax MAR-M-247 in the turbine vanes, A286 for the disk and shaft, Haynes 242 for the turbine housings and Inconel 718 for the pump housing, impeller and inducer. Additional trade studies, conducted later in the program, resulted in changes to some of the materials.

The PDR presentation, discussed in detail at the design review, is included in this section.

UNITED TECHNOLOGIES
PRATT & WHITNEY

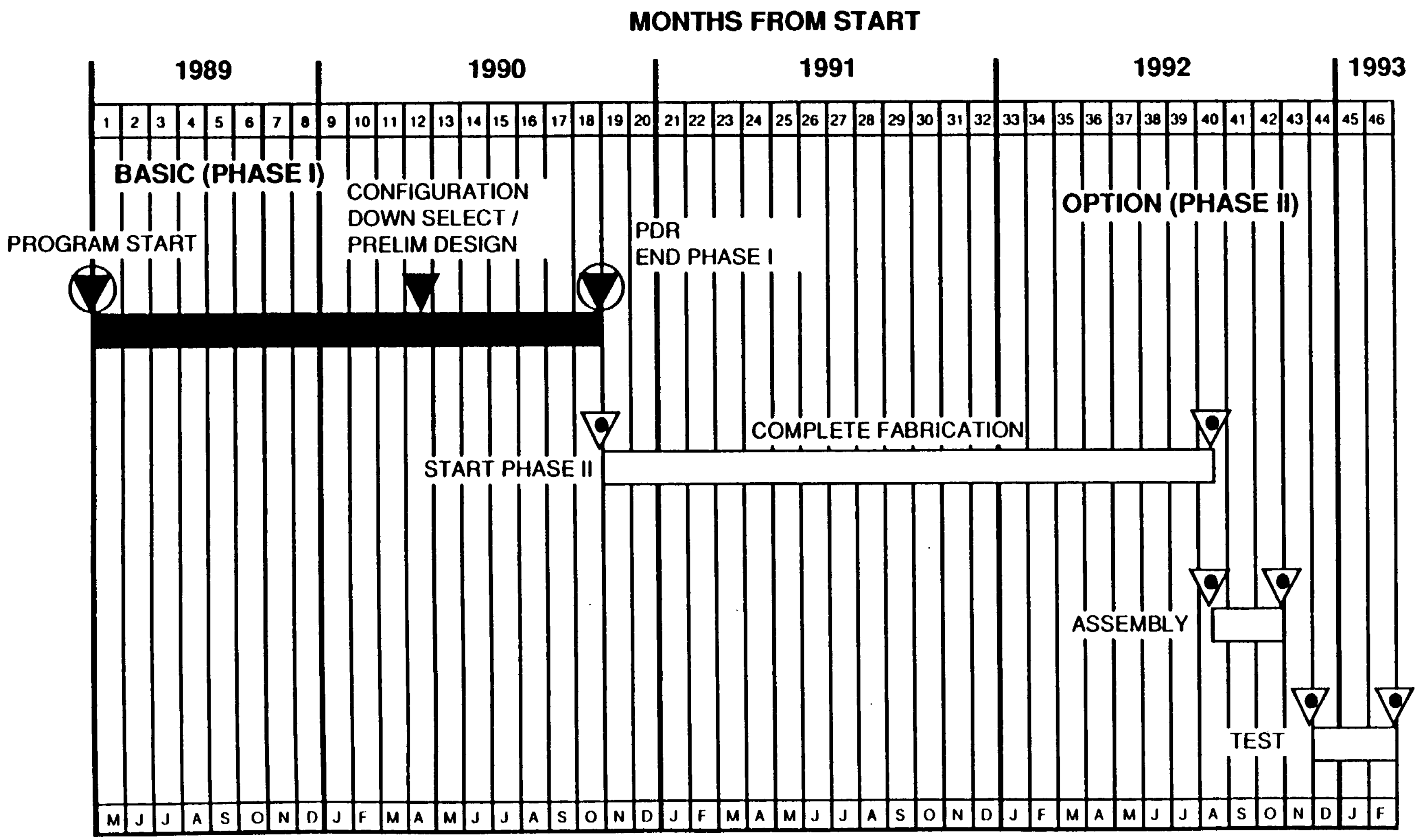
ADP LIQUID OXYGEN TURBOPUMP PDR

PURPOSE OF MEETING

TO PRESENT AND DISCUSS THE OXYGEN TURBOPUMP DESIGN TRADE STUDIES & FABRICATION EVALUATIONS CONDUCTED DURING PHASE I OF THE ADP PROGRAM

ADP LIQUID OXYGEN TURBOPUMP PDR

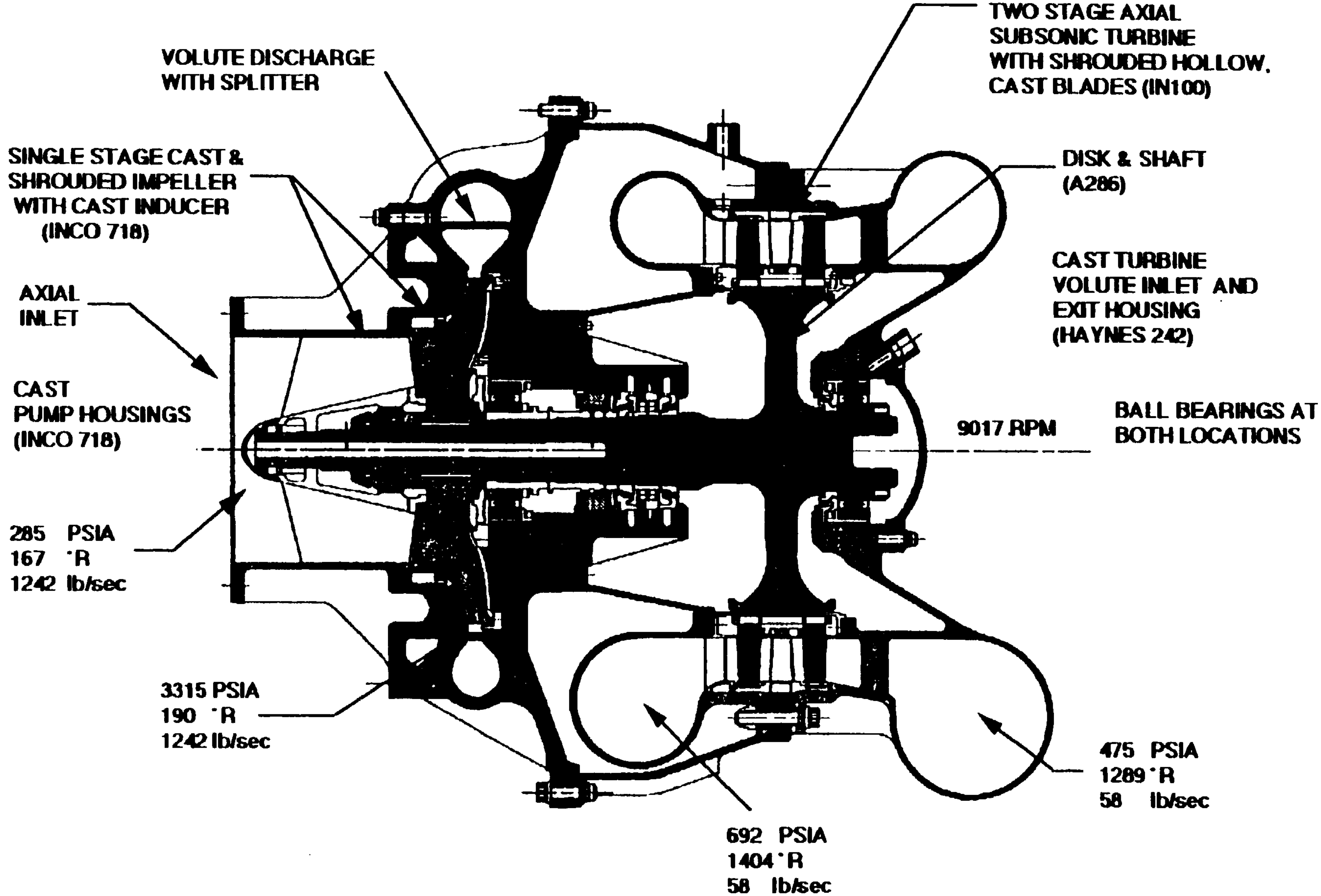
SCHEDULE



ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES PRATT & WHITNEY

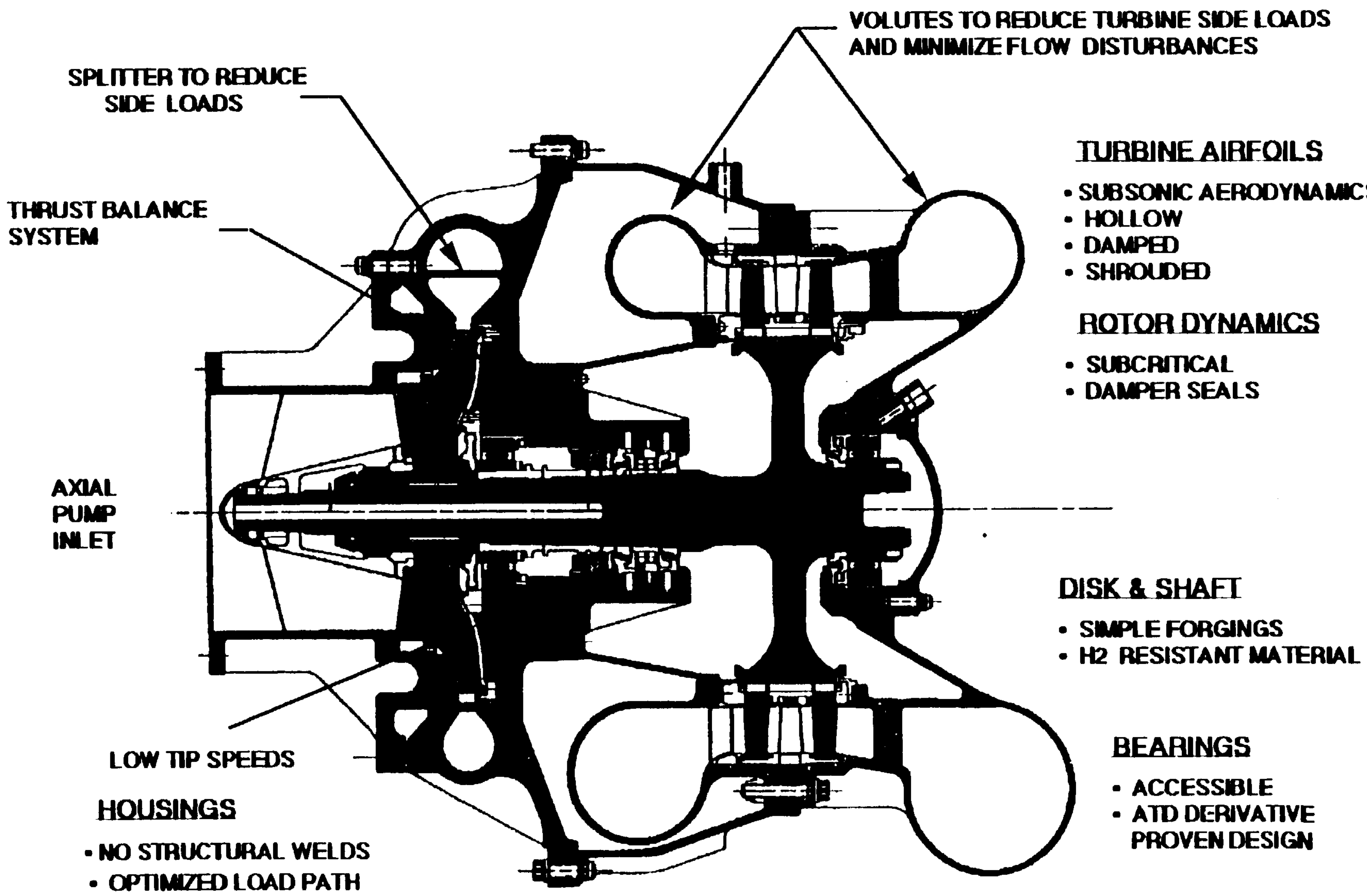
BASELINE CONFIGURATION @ MDC



ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES
PRATT & WHITNEY

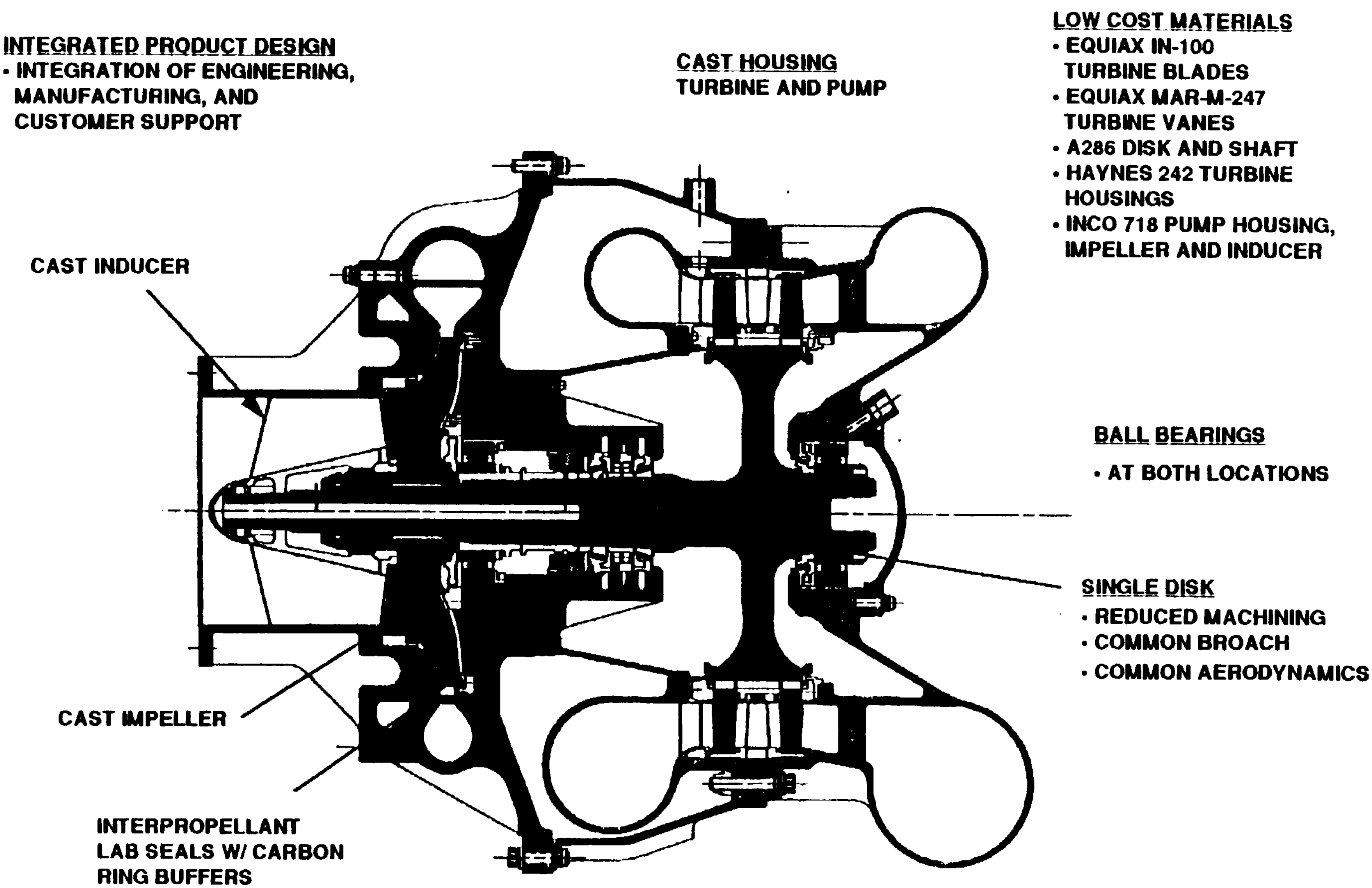
RELIABILITY FEATURES



ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES PRATT & WHITNEY

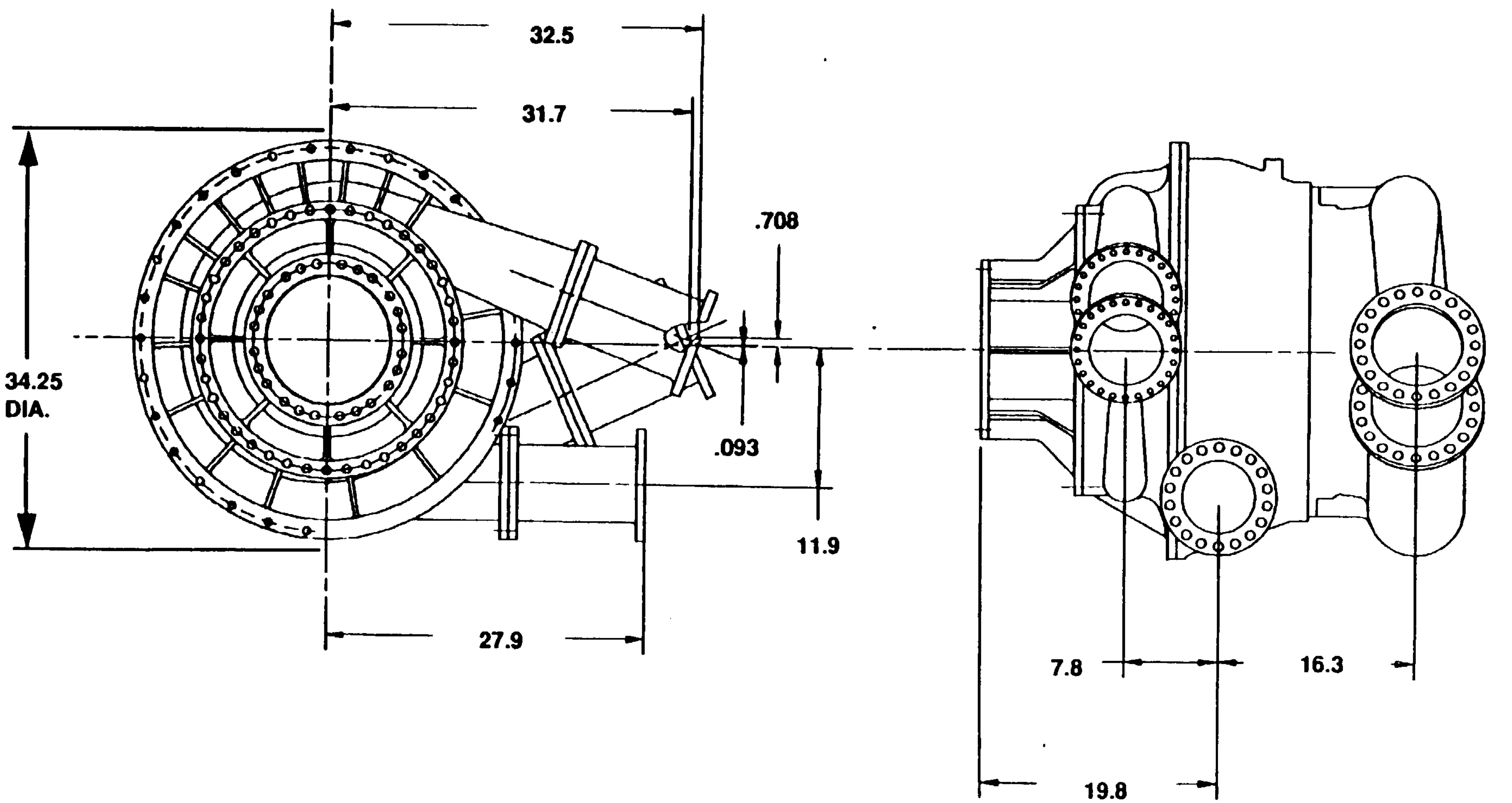
LOW COST FEATURES



UNITED TECHNOLOGIES PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

ICD FEATURES

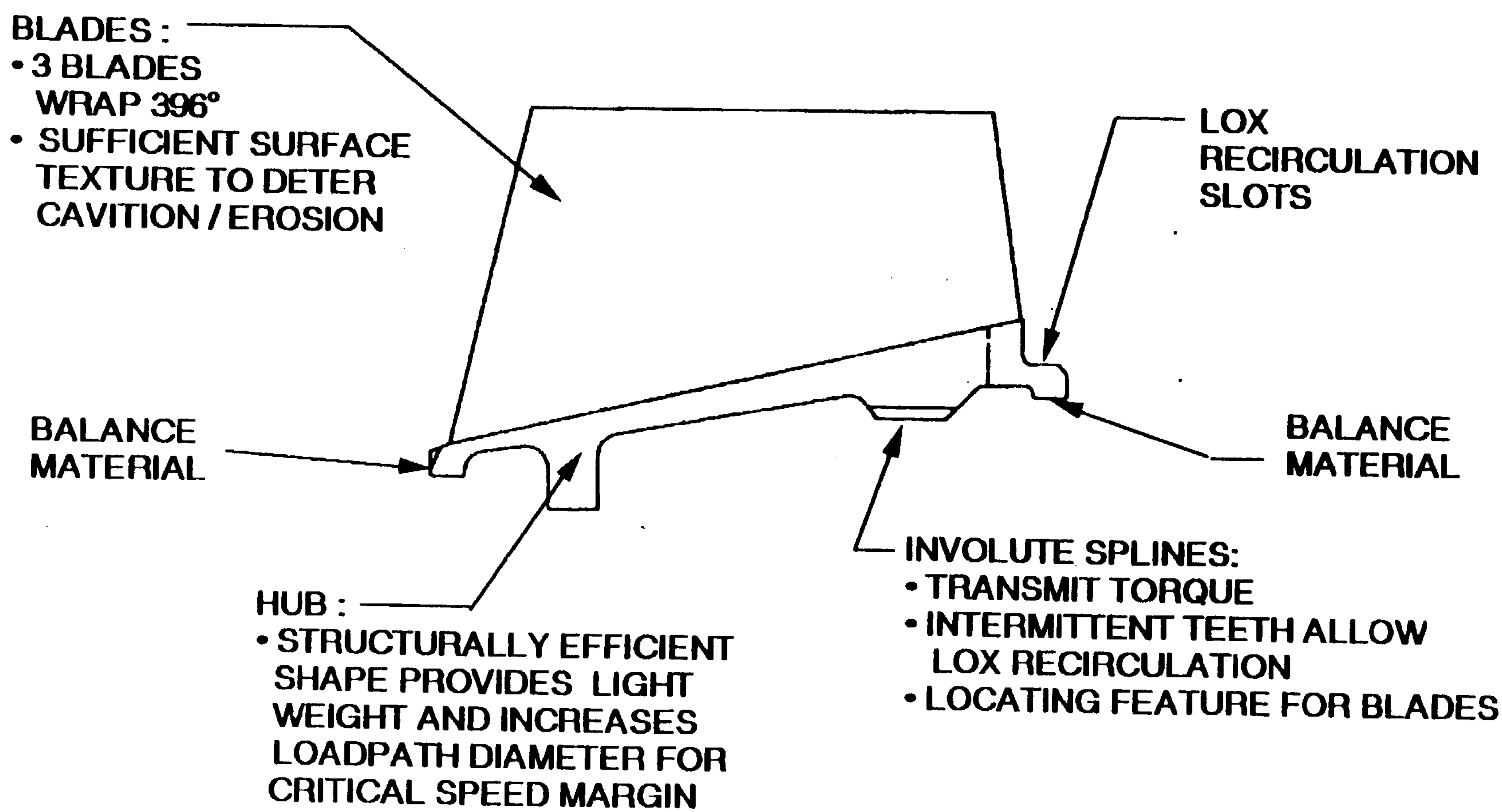


ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES
PRATT & WHITNEY

LIGHT WEIGHT YET STRUCTURALLY ROBUST INDUCER

MATERIAL : CAST FINE GRAIN INCO 718

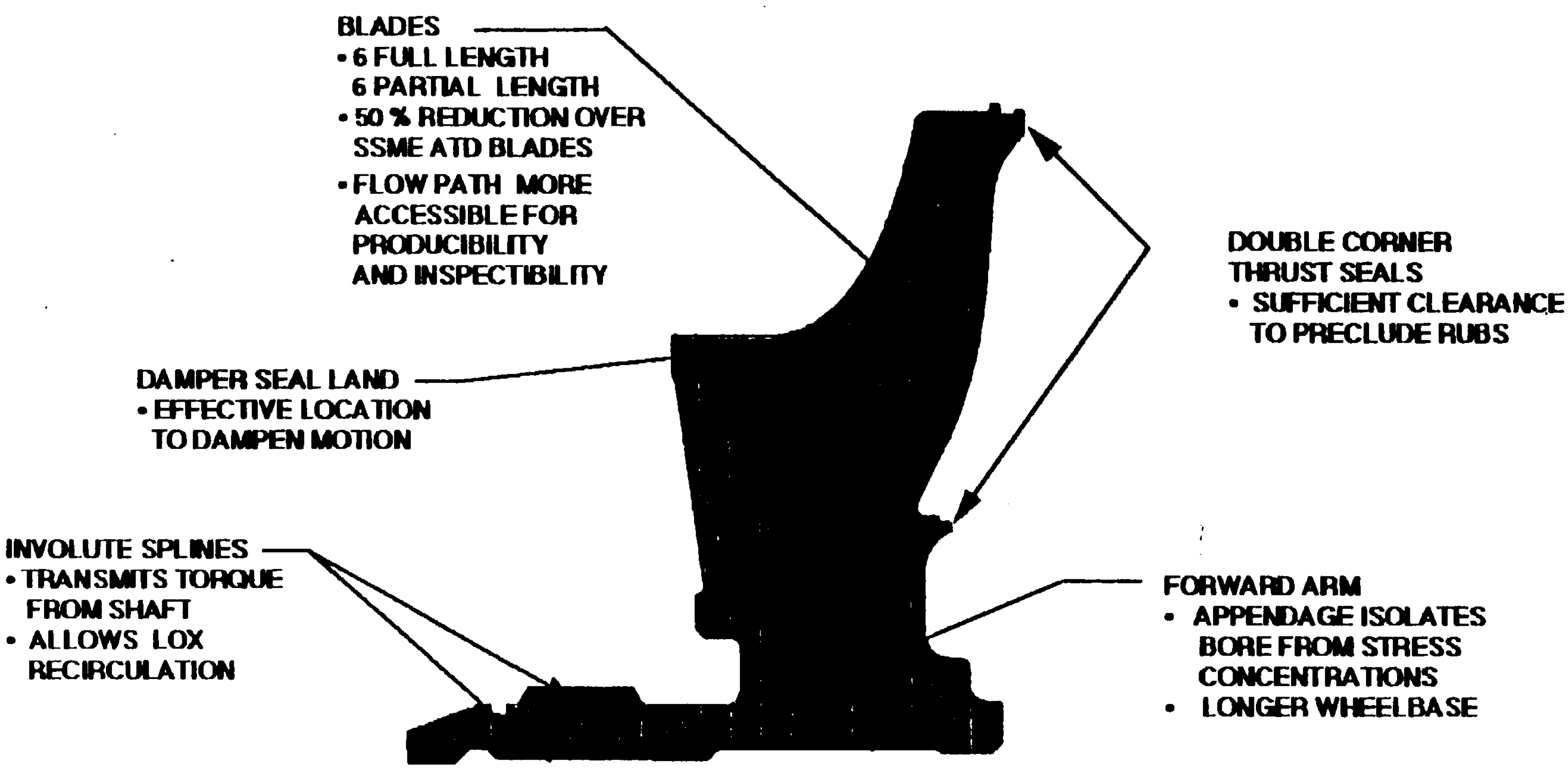


ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES PRATT & WHITNEY

CAST IMPELLER SIGNIFICANTLY REDUCES FABRICATION COST

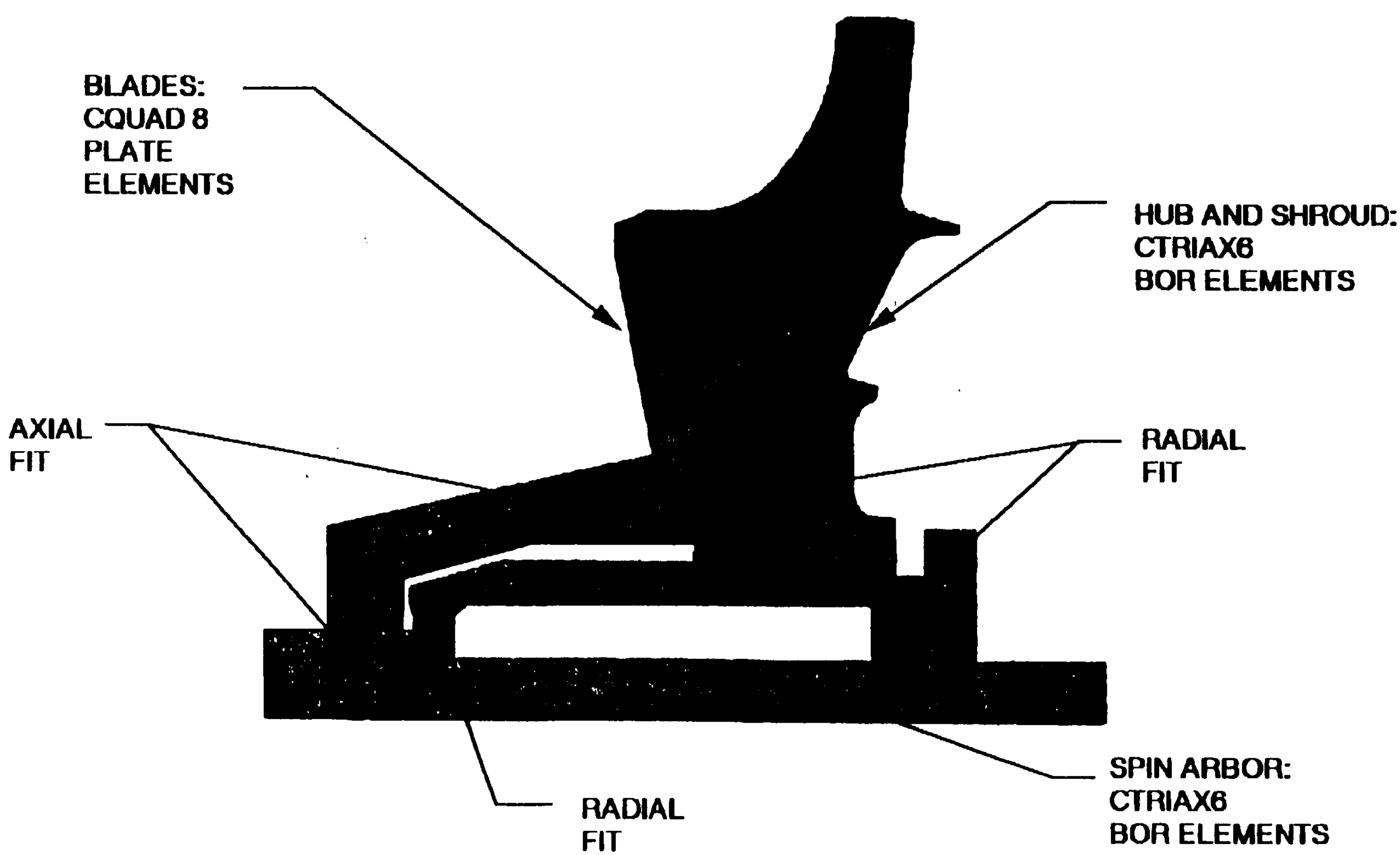
MATERIAL: CAST FINE GRAIN INCO 718



ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES PRATT&WHITNEY

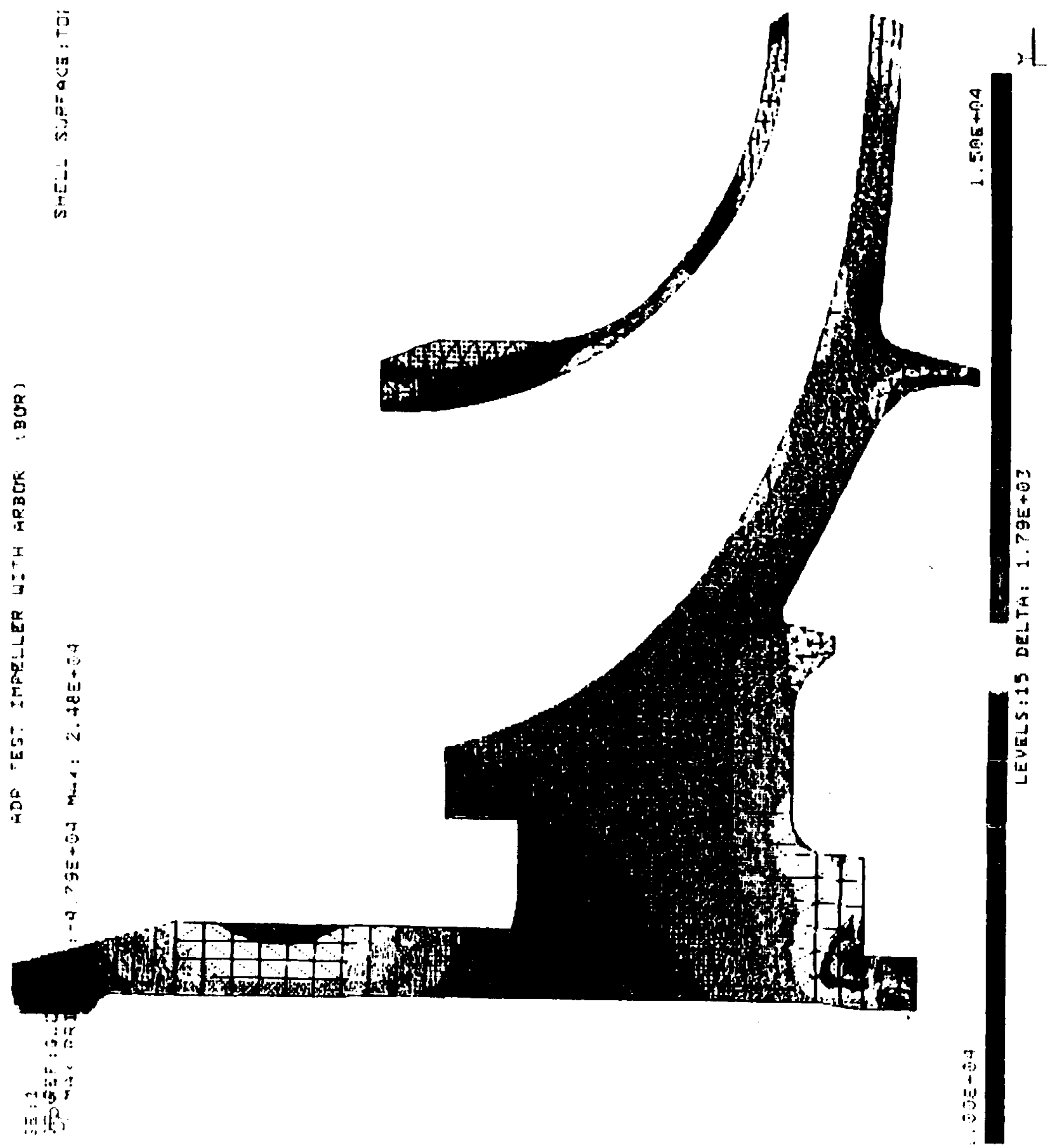
NASTRAN FINITE ELEMENT MODEL SIMULATES INSTALLED IMPELLER



UNITED TECHNOLOGIES
PRATT&WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

STRUCTURAL ANALYSIS SHOWS STRESSES WITHIN DESIGN CRITERIA



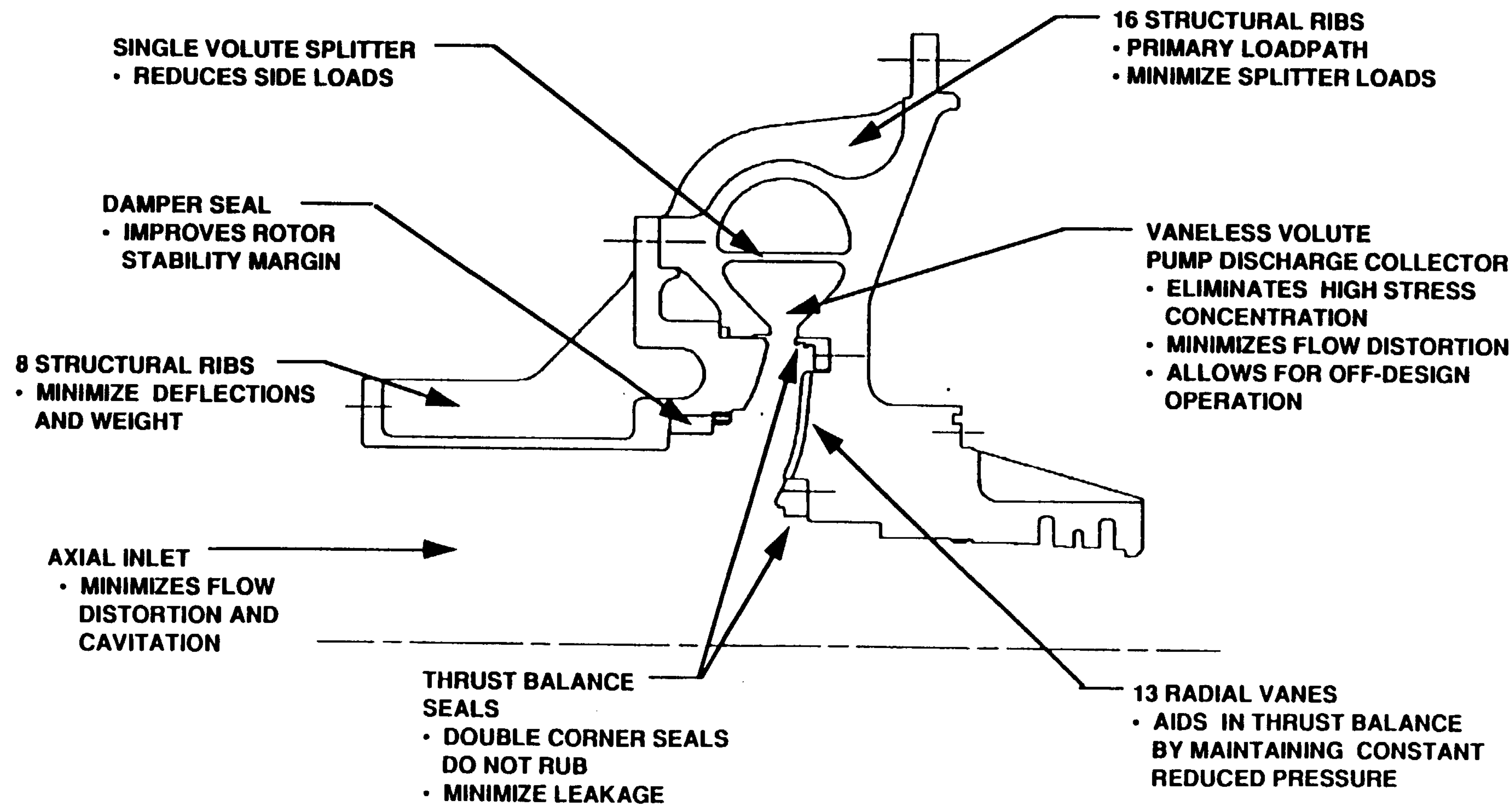
ORIGINAL PAGE IS
OF POOR QUALITY

UNITED TECHNOLOGIES
PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

PUMP INLET AND DISCHARGE HOUSINGS MINIMIZE FLOW DISTORTION, THEREBY, REDUCING BEARING LOADS

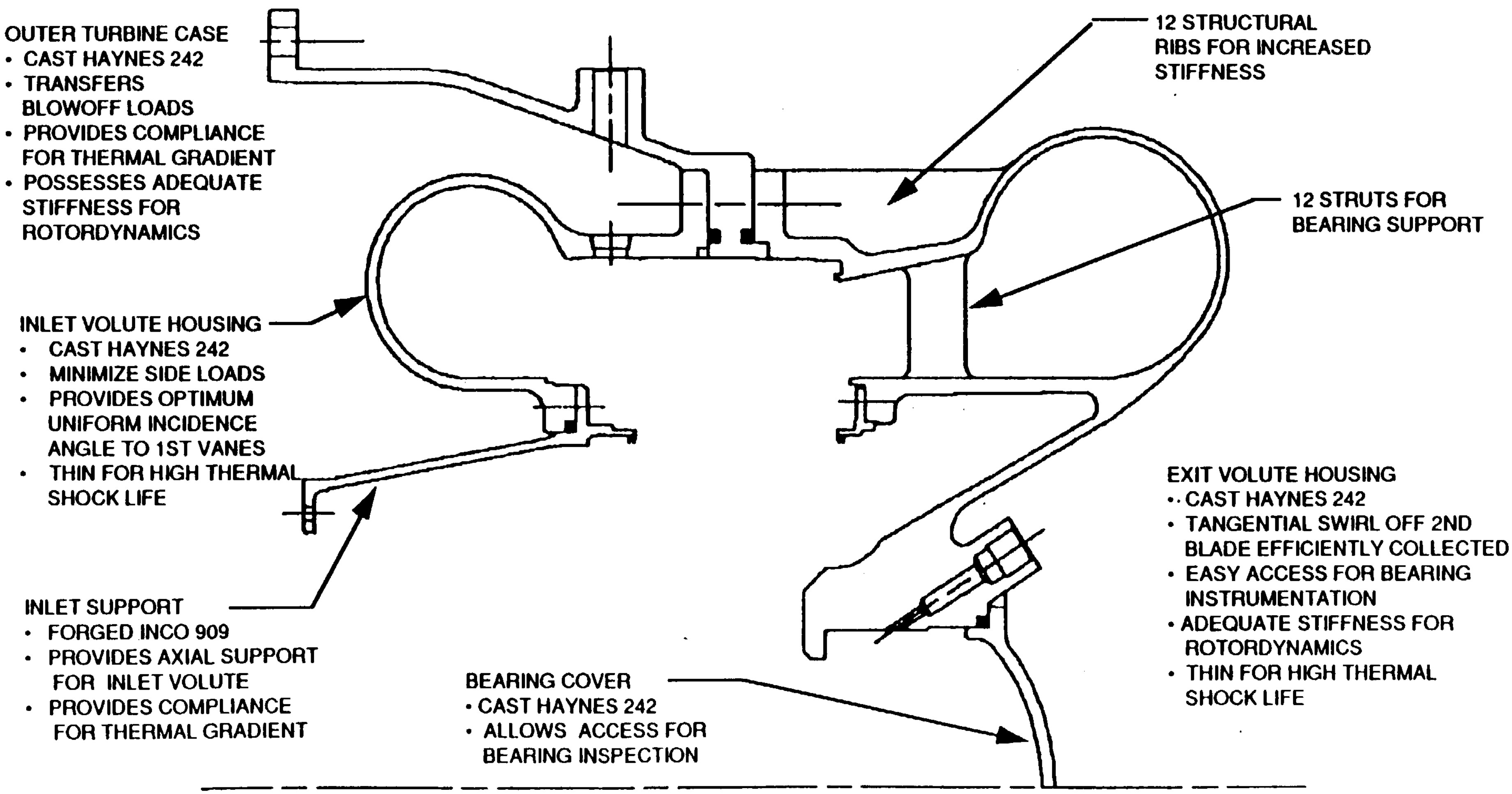
MATERIAL - CAST FINE GRAIN INCO 718



UNITED TECHNOLOGIES PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

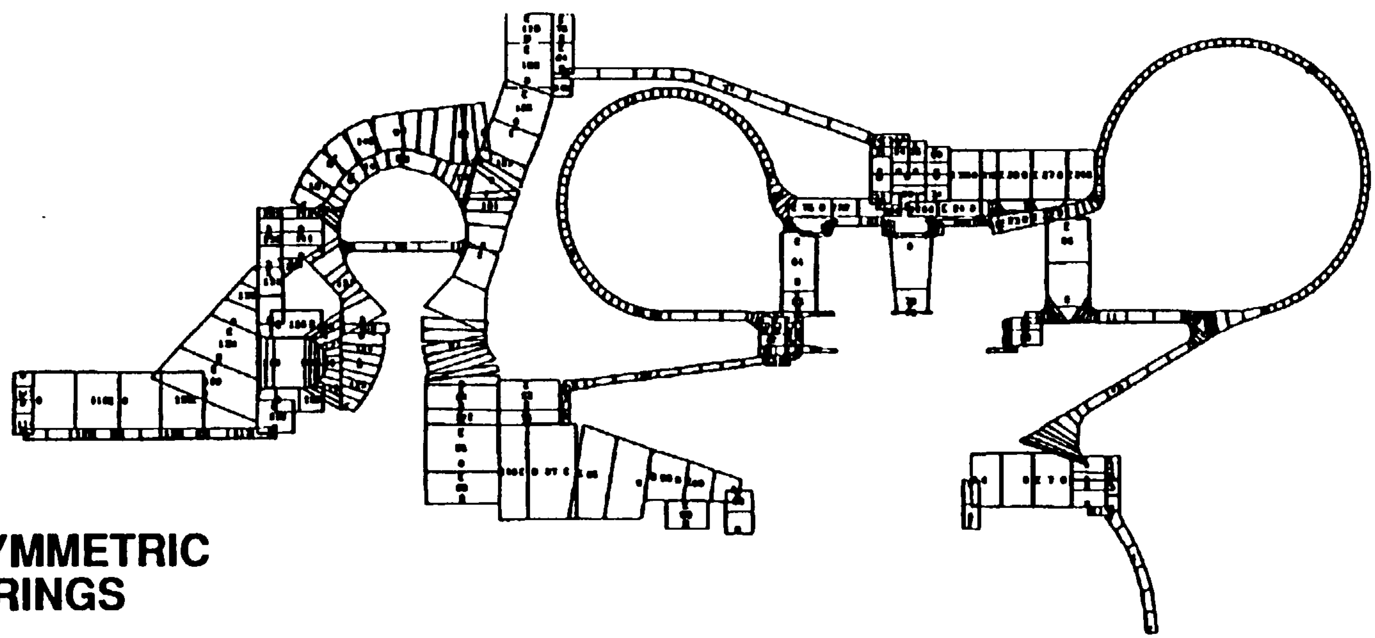
TURBINE HOUSINGS PROVIDE MINIMAL FLOW DISTORTION , EXCELLENT LOADPATHS



UNITED TECHNOLOGIES PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

COMPLETE STRUCTURAL HOUSING SHELL MODEL PROVIDES BETTER CORRELATION BETWEEN INDIVIDUAL HOUSINGS

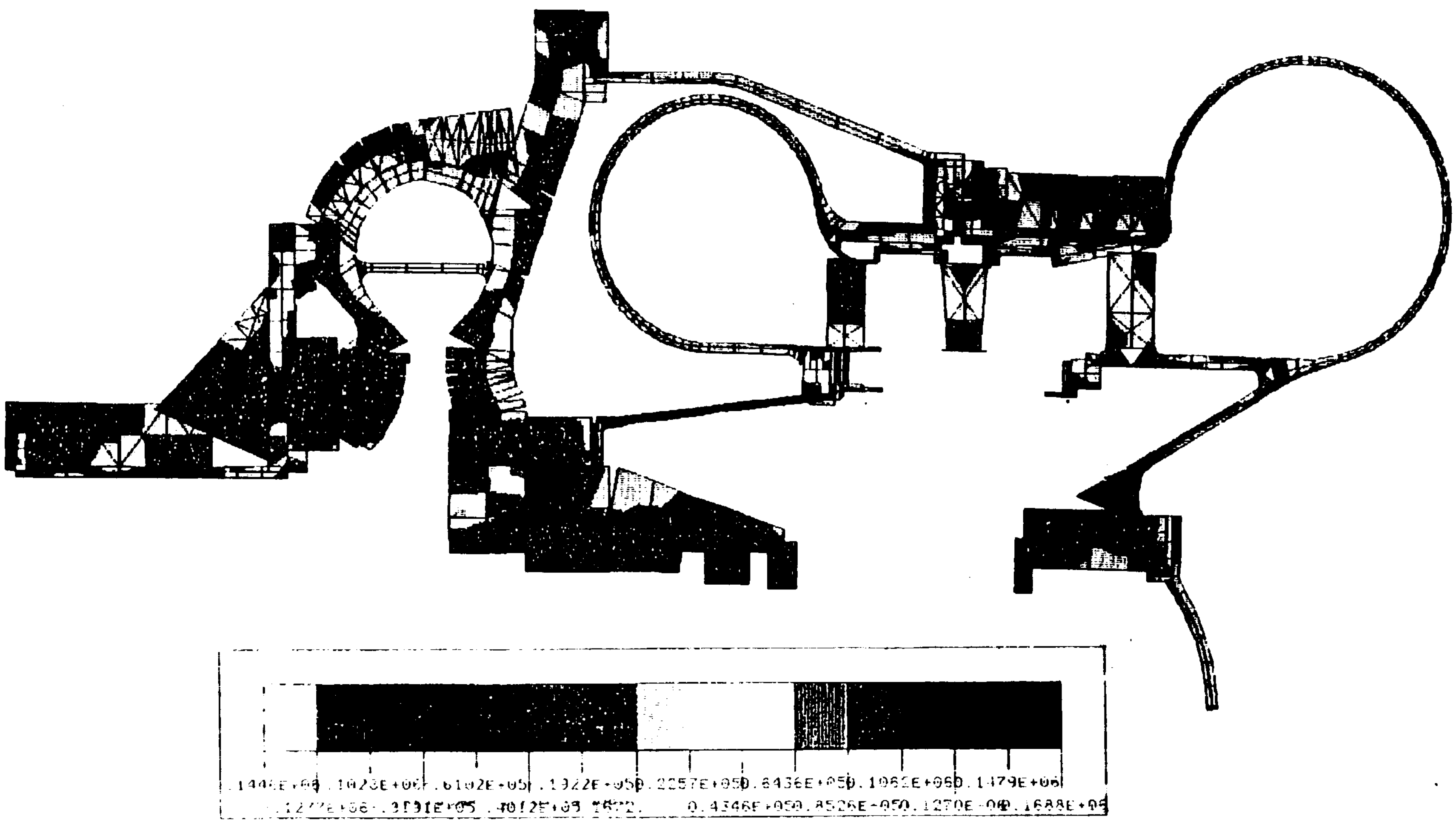


- AXISYMMETRIC THIN RINGS
- MAXIMUM DESIGN CONDITION PARAMETERS OF PRESSURES AND TEMPERATURES

UNITED TECHNOLOGIES
PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

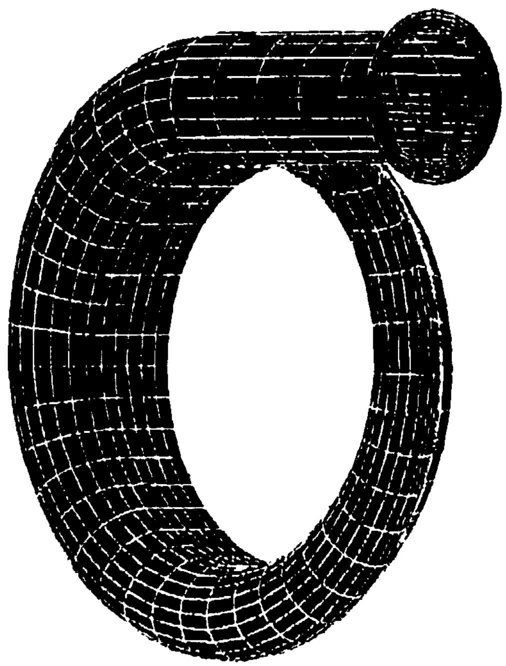
STRESS ANALYSIS POINTS OUT PROBLEM AREAS



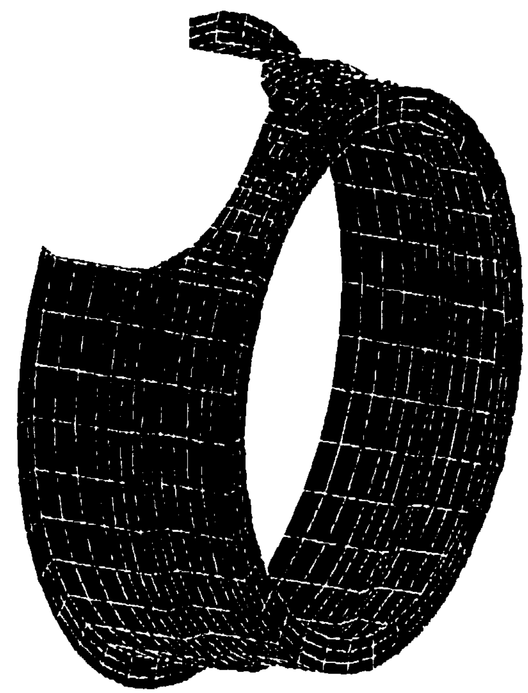
ORIGINAL PAGE IS OF POOR QUALITY

ADP LIQUID OXYGEN TURBOPUMP PDR

NASTRAN PLATE ELEMENT MODEL FOR TURBINE INLET HOUSINGS AND OUTER CASE PROVIDES INSIGHT INTO NON-SYMMETRIC GEOMETRIES



TURBINE INLET HOUSING

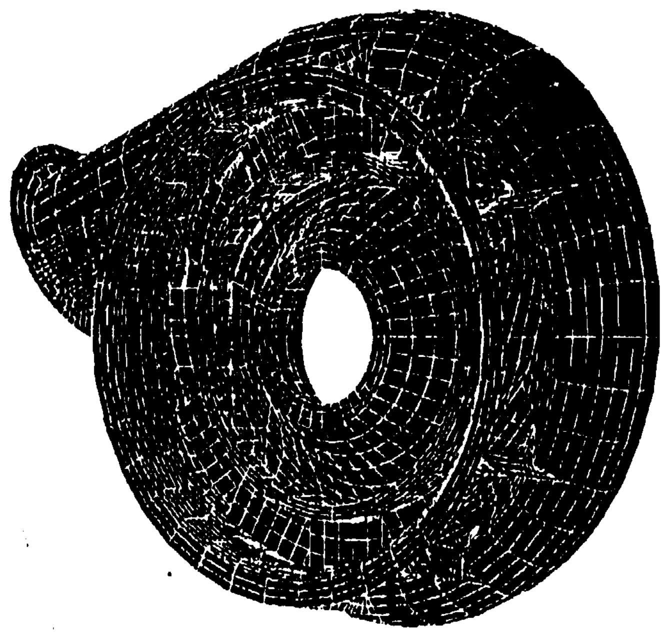


OUTER TURBINE CASE

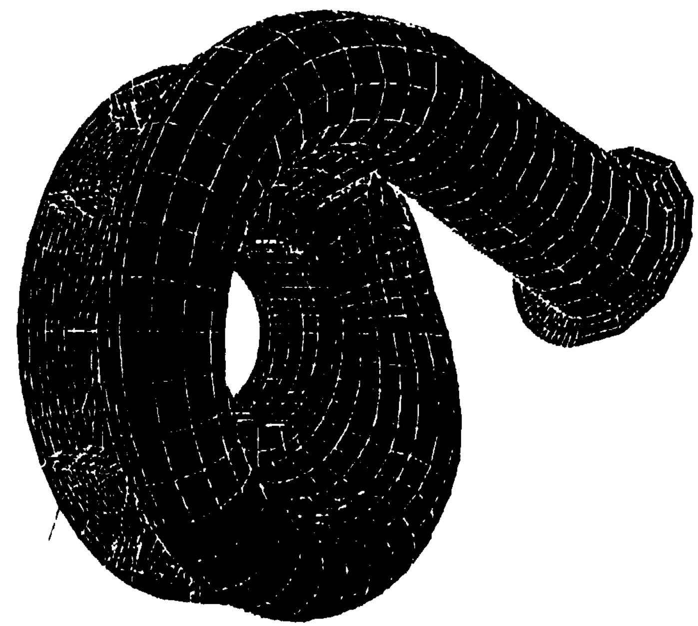
UNITED TECHNOLOGIES PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

NASTRAN PLATE ELEMENT MODEL NEARS COMPLETION FOR EXIT VOLUTE HOUSING



FRONT VIEW



REAR VIEW

UNITED TECHNOLOGIES
PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

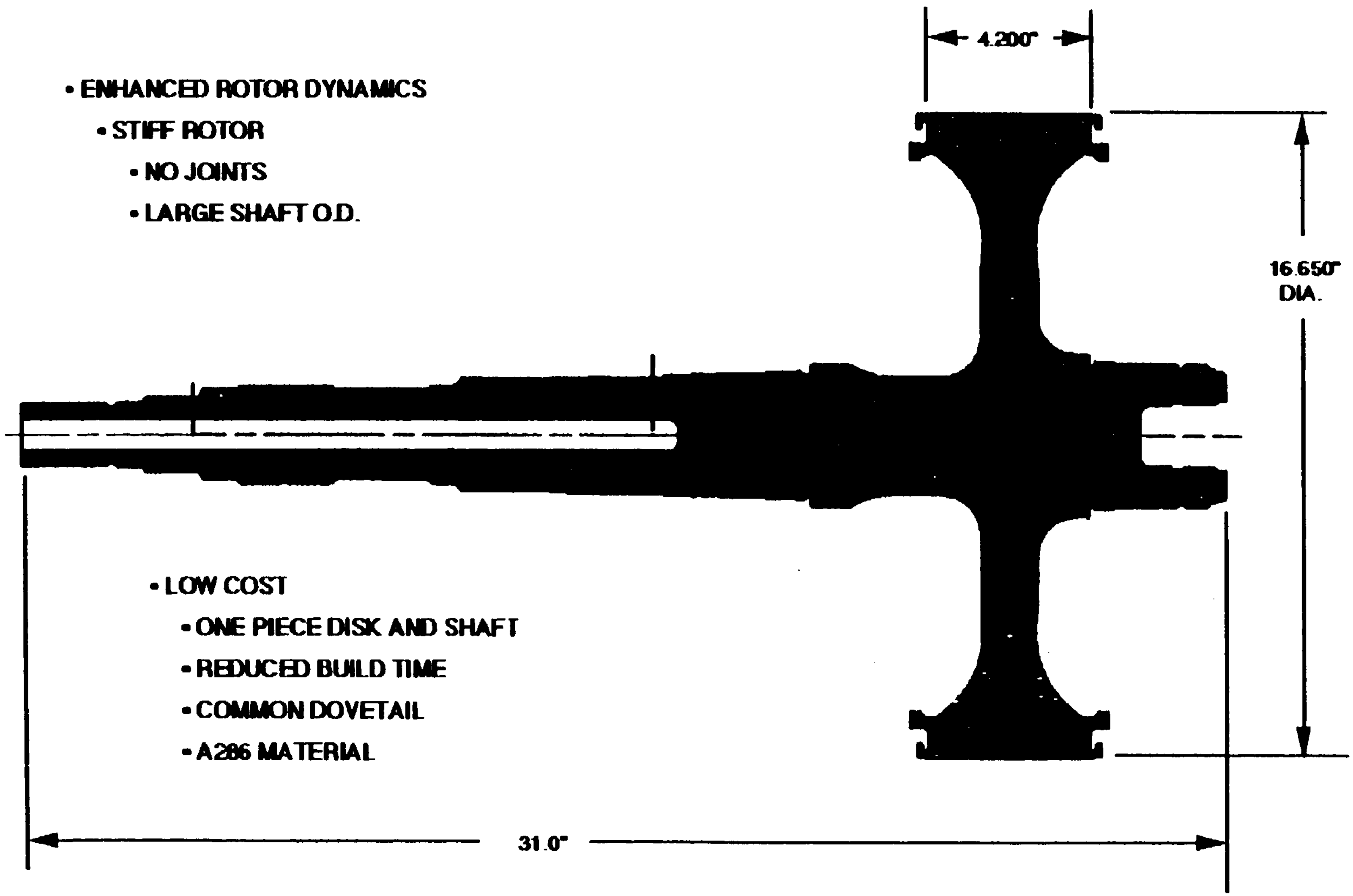
ADDITIONAL ANALYSIS TO BE COMPLETED IN DETAIL DESIGN PHASE

- INDUCER
  - 3D BLADE STRUCTURAL ANALYSIS
  - BLADE VIBRATORY ANALYSIS
- IMPELLER
  - 3D STRUCTURAL ANALYSIS
  - VIBRATORY ANALYSIS
- PUMP HOUSINGS
  - 3D STRUCTURAL ANALYSIS
- TURBINE HOUSINGS
  - 3D STRUCTURAL ANALYSIS
- COMPLETE CLEARANCE ANALYSIS

ADP LIQUID OXYGEN TURBOPUMP PDR

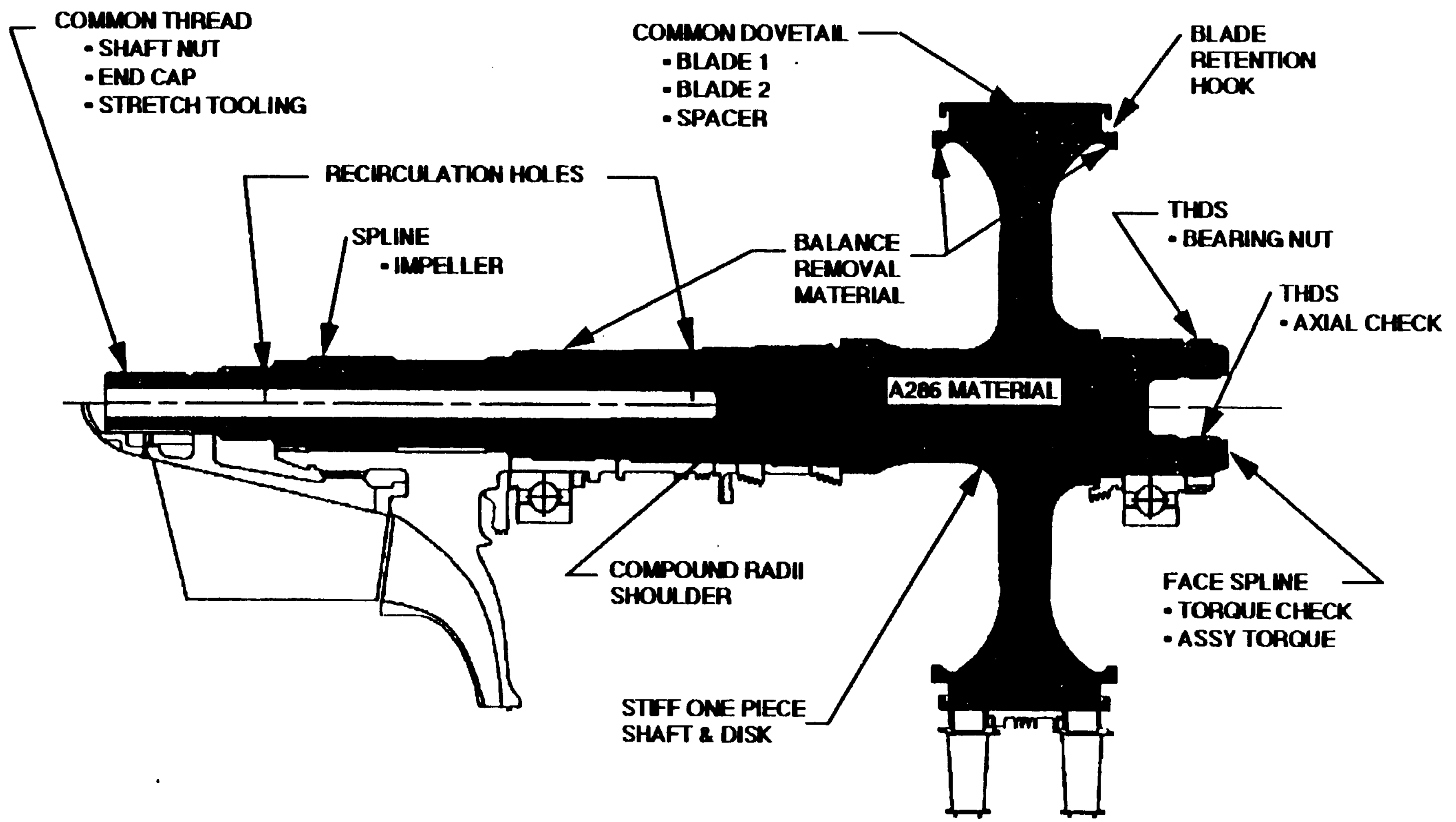
DISK & SHAFT - CONFIGURATION

- ENHANCED ROTOR DYNAMICS
  - STIFF ROTOR
    - NO JOINTS
    - LARGE SHAFT O.D.



- LOW COST
  - ONE PIECE DISK AND SHAFT
  - REDUCED BUILD TIME
  - COMMON DOVETAIL
  - A286 MATERIAL

DISK & SHAFT - FEATURES

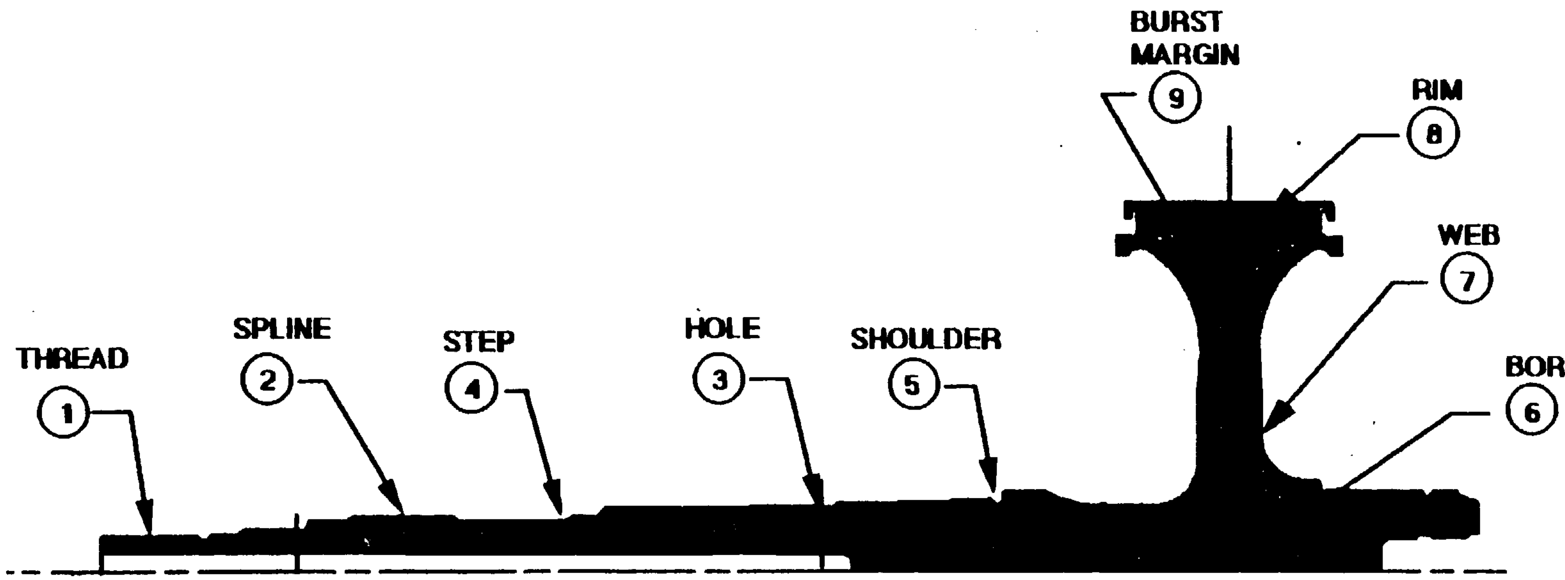


ADP LIQUID OXYGEN TURB0PUMP PDR

UNITED TECHNOLOGIES
PRATT & WHITNEY

LIMITING SAFETY MARGINS AND LIVES LOCATION

THE TURBINE DISK AND SHAFT'S MOST CRITICAL MARGINS AND LIVES LOCATIONS.



ADP LIQUID OXYGEN TURBO PUMP PDR

DISK AND SHAFT GREATLY EXCEEDS DURABILITY REQUIREMENTS

- HIGH SAFETY MARGINS
- HIGH LCF MARGIN

					MARGINS OF SAFETY			
LOC.	TEMP. DEG F.	.2% YIELD KSI	ULTIMATE KSI	OPERATING STRESS KSI	YIELD S.F.=1.1	ULTIMATE S.F.=1.4	CONDITIONS	LCF LIFE CYCLES
1	70	100	145	59 KT = 3.0	0.53	.74	NOTE 3	>1,000
2	-280	120	173	61 KT = 2.49	0.79	1.03	NOTE 2	>1,000
3	-280	120	173	45 KT = 3.87	1.4	2.72	NOTE 2	>1,000
4	-280	120	173	63 KT = 1.31	0.74	0.97	NOTE 2	>1,000
5	70	100	145	34 KT = 2.38	1.70	2.08	NOTE 2	>1,000
6	70	100	145	32 KT = 1.00	2.77	3.29	NOTE 2	>1,000
7	70	100	145	51 KT = 1.400	.78	1.03	NOTE 2	>1,000
8	70	100	145	22 KT = 2.67	3.05	3.61	NOTE 6	>1,000
9	90	N/A	145	35 BURST MARGIN	N/A	1.76 NOTE 4	NOTE 2	N/A

TABLE 1 TURBINE DISK AND SHAFT STRESS/LIFE SUMMARY TABLE

NOTES:

1. THIS TABLE SUMMARIZES THE MOST CRITICAL LIVES AND SAFETY MARGINS
2. MEG060689 CYCLE - VERSION 3, MAXIMUM DESIGN CONDITIONS, 9,017 RPM
3. 70° PRELOADED ASSEMBLY CONDITIONS, 0 RPM
4. ULTIMATE S.F. = 1.5
5. N/A = NOT APPLICABLE
6. WORST ACCEL TRANSIENT, 9,017 RPM

ADP LIQUID OXYGEN TURBOPUMP PDR

UNITED TECHNOLOGIES
PRATT & WHITNEY

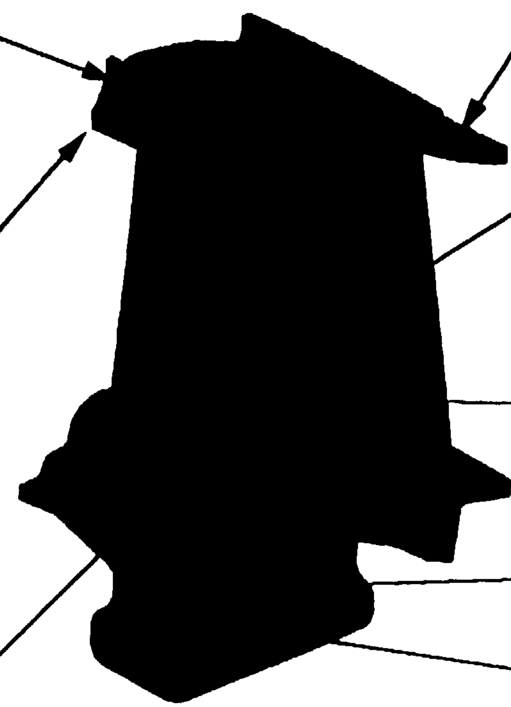
BLADE FEATURES SELECTED FOR HIGH RELIABILITY, LOW COST

COMMON BLADE
- REDUCED COST DUE TO INCREASED PRODUCTION AND ELIMINATION OF P/N

KNIFE EDGES
- FOR LOW TIP LEAKAGE
- COMPATIBLE WITH HONEYCOMB ABRADABLE SEAL LANDS

CONTOURED SHROUD EDGES
- PRODUCED BY SIMULTANEOUS MACHINING WITH PLATFORM
- SHAPE REDUCES SHROUD STRESSES AND TAILORS SHROUD RESONANCE FREQUENCIES

TAPERED WALL THICKNESSES
- LOWERS ROOT STRESSES
- ALLOWS TAILORING OF BLADE RESONANCES FREQUENCIES



SHROUDED
- REDUCED SENSITIVITY TO OFF-DESIGN TIP CLEARANCES
- REDUCED NUMBER OF BLADES
- REDUCED TURBINE DIAMETER

(IN100) EQUIAXED MATERIAL
- RAISES RESONANT FREQUENCY
- REDUCED DENSITY FOR ROTORDYNAMIC MARGIN
- LOW COST
- LARGE EXPERIENCE BASE

HOLLOW A/F
- INSENSITIVE TO THERMAL TRANSIENT
- 31% PULL REDUCTION

ELLIPTICAL FILLET RADII
- MINIMIZES Kt'S

DOVETAIL ATTACHMENT
- KNOWN LOAD SPLIT
- INSENSITIVE TO RADIAL THERMAL GRADIENTS
- LOWER INITIAL TOOLING COSTS

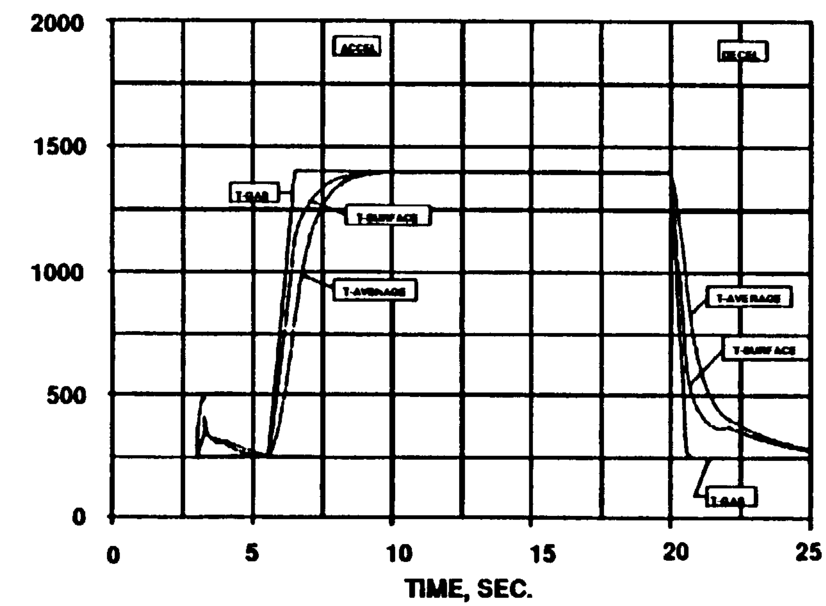
DAMPED
- RELIABILITY

UNITED TECHNOLOGIES PRATT & WHITNEY

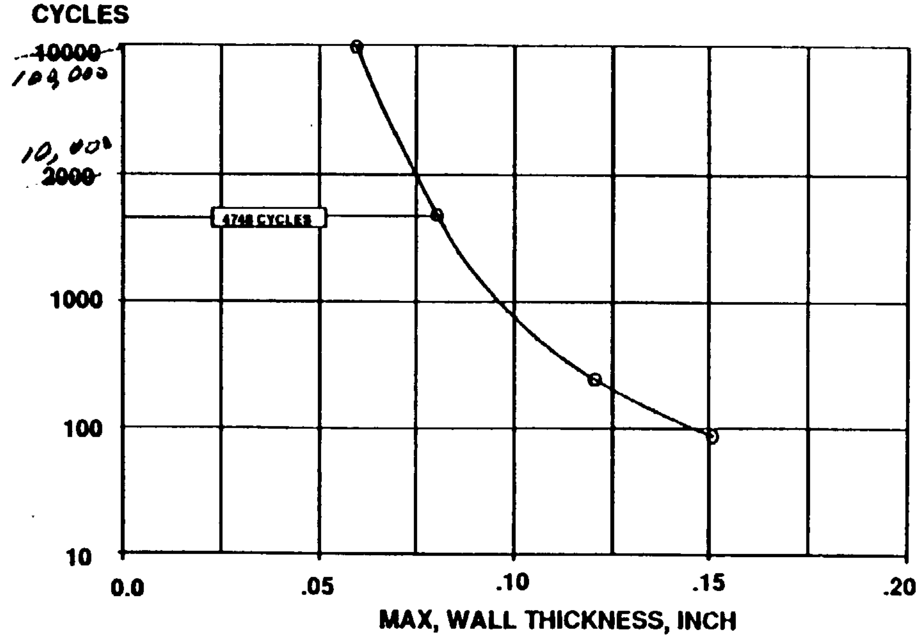
ADP LIQUID OXYGEN TURBOPUMP PDR

HOLLOW AIRFOIL PROVIDES LARGE LIFE MARGINS

ADP LOX TURBINE BLADE (PWA658, 0.080" THICK)
ROCKETDYNE RIG TRANSIENT DATED 8/21/90
TRANSIENT THERMAL RESPONSE



ADP LOX TURBINE BLADE LCF CAPABILITY
PWA 658

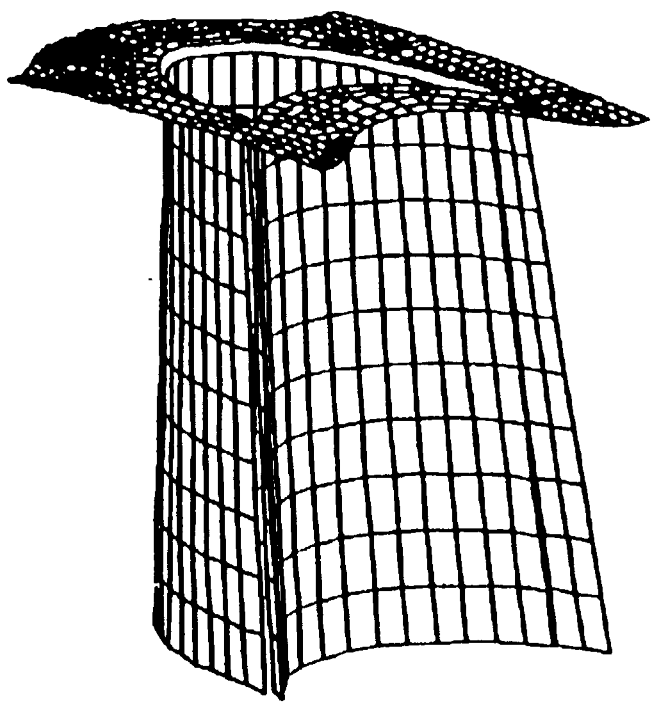


- CURRENT .060-.080 WALL THICKNESS YIELDS >4700 CYCLES LIFE
- LARGE MARGIN MAKES DESIGN INSENSITIVE TO MATERIAL PROPERTIES AND START, SHUTDOWN TRANSIENT VARIABILITY
- BASED ON 1-D ANALYSIS USING ADIABATIC CONDITIONS IN CORE CAVITY WITH EXTERNAL AIRFOIL HEAT TRANSFER COEFFICIENTS VARYING WITH TRANSIENT PRESSURE AND SCRUBBING VELOCITY

UNITED TECHNOLOGIES
PRATT & WHITNEY

ADP OXYGEN TURBOPUMP PRELIMINARY DESIGN REVIEW

ADP 1ST AND 2ND STAGE TURBINE BLADE VIBRATION MODEL



NASTRAN 3-D TURBINE BLADE MODEL
NON-LINEAR DYNAMIC ANALYSIS SUMMARY

ANALYSIS FEATURES:

- IN-100 - BLADE MATERIAL
- A-286 - DISK RIM MATERIAL
- SAME MODEL FOR BOTH STAGES (WORST CASE STUDY)
- NON-LINEAR ANALYSIS WITH CENTRIFUGAL STIFFENING
- MAX TEMPERATURE @ MDC (900° F)
- MAX SPEED (ACCELERATION) @ MDC (9,017 RPM)
- TRANSLATIONS & ROTATIONS FIXED AT DISK RIM
- NASTRAN PLATE AND BEAM ELEMENT MODEL

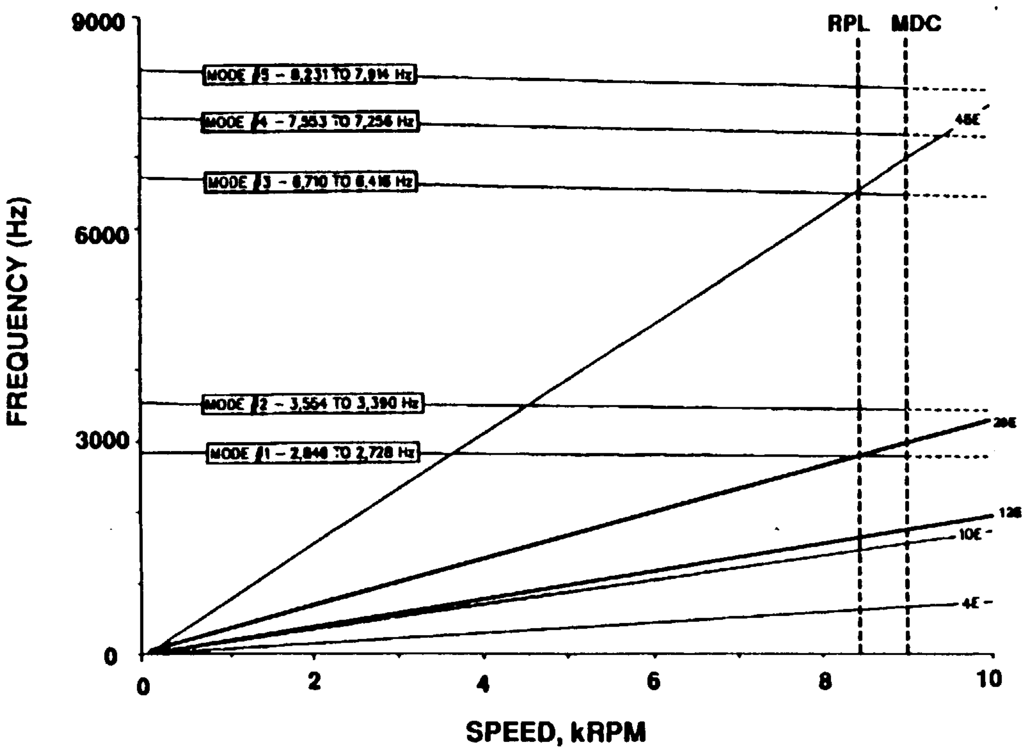
UNITED TECHNOLOGIES PRATT & WHITNEY

ADP LIQUID OXYGEN TURBOPUMP PDR

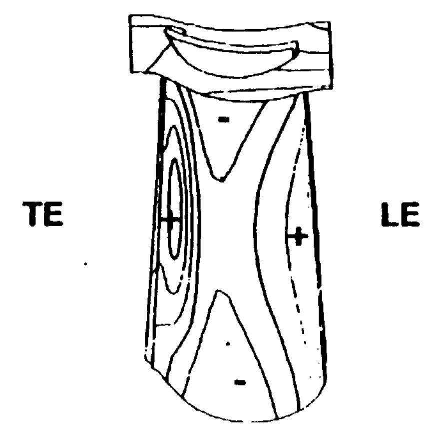
ADP 1ST AND 2ND STAGE TURBINE BLADE CAMBELL DIAGRAM

CAMPBELL DIAGRAM

FIXED @ DISK RIM, W/TEMP & ACCEL EFFECTS
PWA 658 (IN-100) @ 77-900° F



3RD MODE SHAPE



NORMALIZED DISPLACEMENTS
CONTOUR LINE PLOT

"TE TRANSLATION" MODE

- SHIFTING OF THE MODES BY RECONTOURING THE WALL THICKNESS WILL BE TRADED AGAINST CHANGES IN THE VANE COUNT TO PROVIDE A 15% MARGIN ON ALL CROSSINGS IN THE OPERATING RANGE.

2.3 PRELIMINARY COST MODEL

As part of the initial contractual obligations of the Oxidizer Turbopump Advanced Development Program, the architecture for a preliminary cost model was developed. This model, which quantified Operational Production Recurring and Non-recurring costs and Recurring Operations costs, met all of the requirements specified by the ALS Engine Component Statement of Work. It was designed to be user friendly having been based on a Microsoft Excel spreadsheet format which would be run on an Apple Macintosh computer.

The Intent of the program was to permit such basic parameters as thrust and chamber pressure to be input, from which a baseline design would be scaled. Manufacturing data for each part or subassembly would be modified to reflect the new design at a basic level of labor man-hours and material costs. Using P&W manufacturing data including burdens, learning curve and rate effects, costs for the scaled parts would be calculated and summed to reflect total turbopump recurring costs. One of the benefits of this approach was the visibility of the costs of the individual parts broken down into labor, material and purchased parts which would be used to identify the cost drivers. Although at a less detailed level, estimates would also be made of non-recurring costs such as tooling, support equipment and manufacturing facility requirements.

The Turbopump Operations section of the cost model was structured to include user input variables such as engine reusability, mission flight schedule, engine performance parameters and number of engines per vehicle. Maintenance tasks would be defined for both reusable and expendable operations and used to determine the associated costs. Reliability data would be developed from which failure rates would be established for each failure mode. This data would be used to predict unscheduled tasks and repair costs and ultimately the probability of a failure leading to a catastrophic event, an engine shutdown or a launch delay and the associated costs for each.

The overall success and accuracy of the cost model in predicting operational production costs depended on the ADP program going forward through the manufacture of the turbopump to provide actual manufacturing data for the model. However, many individual aspects of the cost model were developed and utilized throughout the STBE, and STME programs to predict production costs for individual engine modules.

ALS LIQUID OXYGEN TURBOPUMP

COST MODEL

TOM MAYES
(407) 796-3615

September 15, 1989

OXYGEN TURBOPUMP COST MODEL

AGENDA

- PROPOSED MODEL
- NASA REQUIREMENTS
- COST MODEL ISSUES

OXYGEN TURBOPUMP COST MODEL

COSTS ADDRESSED

- TURBOPUMP OPERATIONAL PRODUCTION COSTS
    - RECURRING COST ELEMENTS
    - NON-RECURRING COST ELEMENTS

- TURBOPUMP OPERATIONS COSTS
    - RECURRING COST ELEMENTS

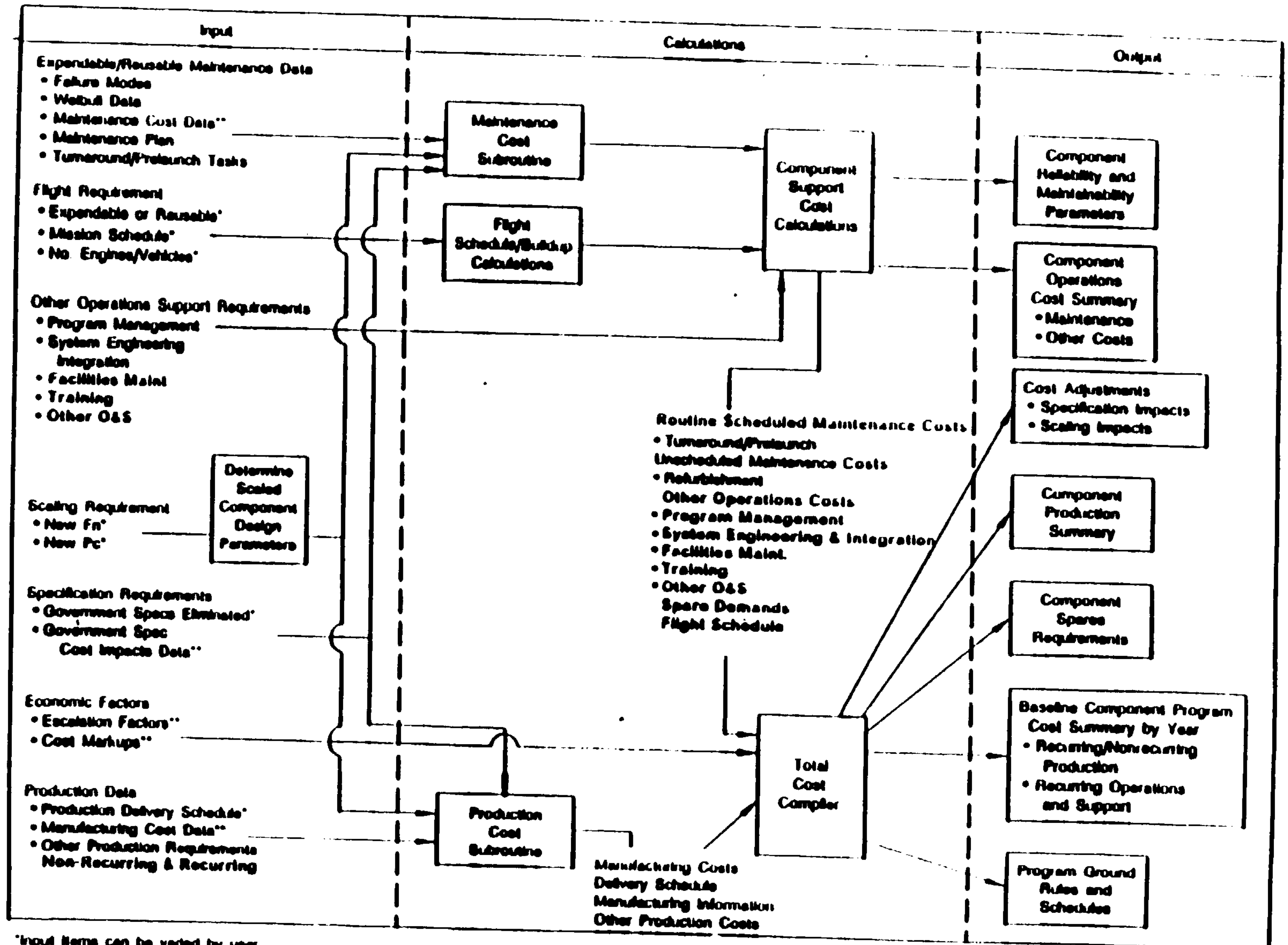
OXYGEN TURBOPUMP COST MODEL

MODEL FEATURES

- PERMITS USER TO CHANGE PROGRAMMATIC GROUND RULES
- PROVIDES COSTS FOR BOTH BASELINE AND SCALED TURBOPUMPS
- DEFINES COST IMPACTS OF GOVERNMENT SPECIFICATION REQUIREMENTS
- HANDLES BOTH REUSABLE AND EXPENDABLE APPLICATIONS
- GIVES COST AND COST RELATED VISIBILITY AT SUBASSEMBLY LEVEL
- EASILY ACCOMODATES UPDATES/CHANGES IN COMPONENT UNIQUE INPUT DATA SETS
- BASES COSTS ON PRODUCTION AT P&W MANUFACTURING FACILITY

OXYGEN TURBOPUMP COST MODEL

SEPARATE SUBROUTINES USED FOR PRODUCTION AND OPERATIONS COSTS



*Input items can be varied by user
**Cost data input in base year dollars. Escalated to desired year dollars

ORIGINAL PAGE IS OF POOR QUALITY

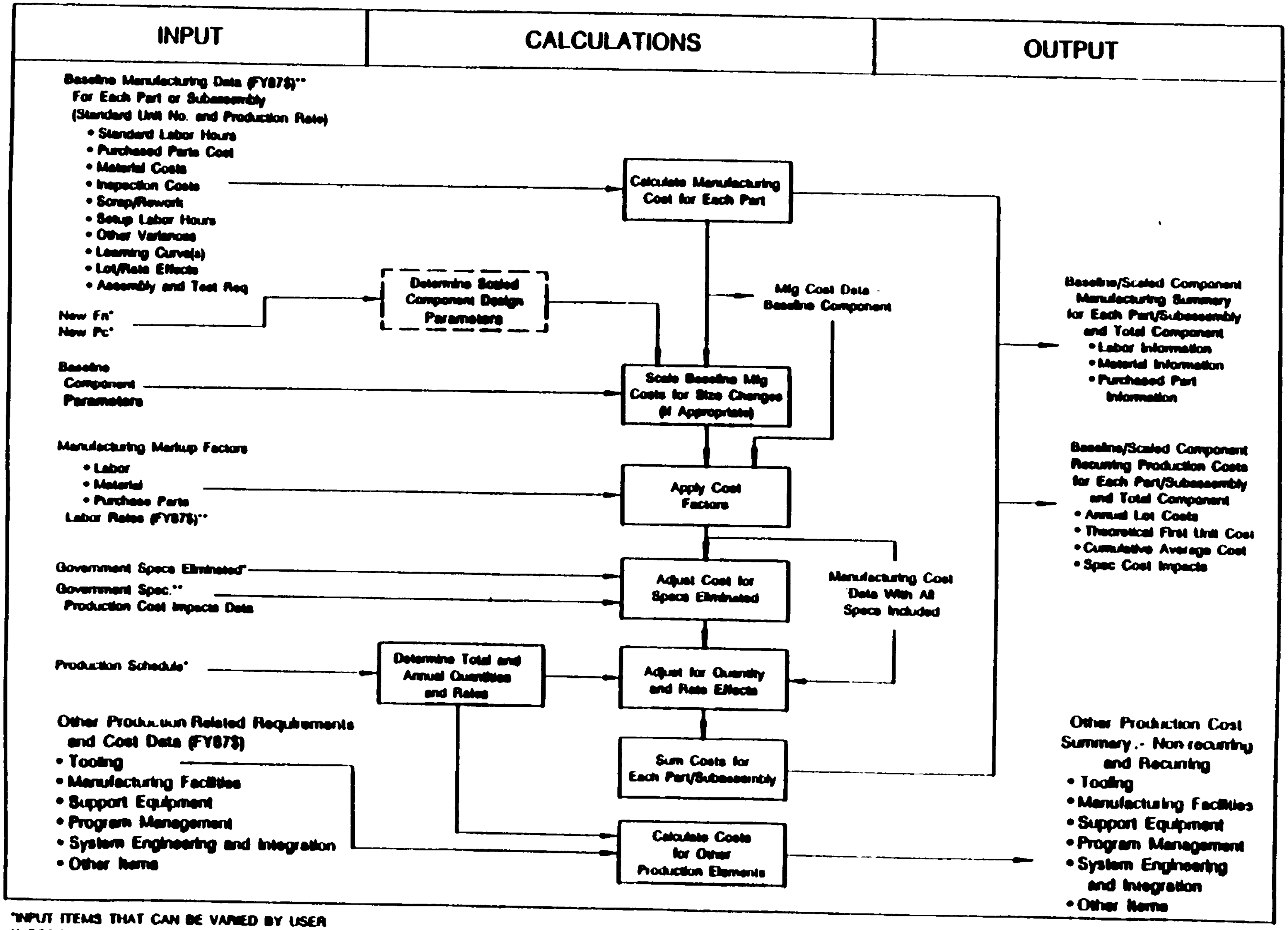
OXYGEN TURBOPUMP COST MODEL

PRODUCTION COST SUBROUTINE

- GENERATES RECURRING PRODUCTION COSTS FROM DETAILED MANUFACTURING INPUT DATA AT COMPONENT/MAJOR SUBASSEMBLY LEVEL
- DEFINES ALL NON-RECURRING AND RECURRING COST ELEMENTS FOR PRODUCTION PHASE
- GIVES VISIBILITY AT SUBASSEMBLY LEVEL
- USER CAN VARY PRODUCTION QUANTITY AND SCHEDULE

OXYGEN TURBOPUMP COST MODEL

PRODUCTION COST SUBROUTINE



*INPUT ITEMS THAT CAN BE VARIED BY USER
** COST DATA INPUT IN FY87$ ESCALATED TO DESIRED YEAR DOLLARS

FDA 357115

ORIGINAL PAGE IS OF POOR QUALITY

OXYGEN TURBOPUMP COST MODEL

PRODUCTION COST INPUTS

USER VARIABLES

ANNUAL PRODUCTION QUANTITY

ESCALATION FACTOR(S)

GOV'T SPECIFICATIONS ELIMINATED

SCALED ENGINE PARAMETERS
- THRUST LEVEL
- CHAMBER PRESSURE

P&W PROVIDED DATA SETS

BASELINE COMPONENT MANUFACTURING DATA (EACH PART/SUBASSEMBLY)

BASELINE COMPONENT DESIGN PARAMETERS

MANUFACTURING LABOR RATES* AND MARKUP FACTORS

GOV'T SPECIFICATIONS PRODUCTION COST IMPACTS DATA*

OTHER PRODUCTION RELATED REQUIREMENTS DATA (NON-RECURRING AND RECURRING)*
- TOOLING
- GROUND SUPPORT EQUIPMENT
- MANUFACTURING FACILITIES
- PROGRAM MANAGEMENT
- SYSTEM ENGINEERING AND INTEGRATION
- OTHER ITEMS (IF APPLICABLE)

*INPUT IN FY '87 DOLLARS

OXYGEN TURBOPUMP COST MODEL

PRODUCTION COST OUTPUT DATA

BASELINE/SCALED MANUFACTURING SUMMARY*

- LABOR
- MATERIAL
- PURCHASED PARTS

BASELINE/SCALED RECURRING PRODUCTION COST SUMMARY

- ANNUAL LOT COSTS
- THEORETICAL FIRST UNIT COST
- TOTAL CUMULATIVE AVERAGE COST
- SPECIFICATION COST IMPACTS

BASELINE/SCALED OTHER PRODUCTION COST SUMMARY - NON-RECURRING/RECURRING

- TOOLING
- GROUND SUPPORT EQUIPMENT
- MANUFACTURING FACILITIES
- PROGRAM MANAGEMENT
- SYSTEM ENGINEERING AND INTEGRATION
- OTHER ITEMS (IF APPLICABLE)

* FOR EACH PART/SUBASSEMBLY AND TOTAL COMPONENT

OXYGEN TURBOPUMP COST MODEL

INCLUDED IN BASELINE TURBOPUMP MANUFACTURING INPUT DATA

FOR EACH PART/SUBASSEMBLY AT STANDARD UNIT NO. AND PRODUCTION RATE

- STANDARD LABOR HOURS
- PURCHASED PARTS COSTS
- MATERIAL COSTS
- INSPECTION COSTS
- SCRAP/REWORK
- SETUP LABOR HOURS
- OTHER VARIANCES
- LEARNING CURVE(S)
- LOT/RATE EFFECTS
- ASSEMBLY AND TEST REQUIREMENTS
- LABOR BURDEN FACTORS
- MATERIAL BURDEN FACTORS
- PURCHASED PART BURDEN FACTORS
- OTHER MARKUP (G&A, COST OF MONEY, EAPS, ETC.)

OXYGEN TURBOPUMP COST MODEL

SUPPLIER COST DATA

- HIGH VOLUME PRODUCTION COST DATA (FOR EXPENDABLE ENGINES)
  - THEORETICAL FIRST UNIT COST
  - COST IMPROVEMENT SLOPE
  - CUMULATIVE AVERAGE COST FOR 3000 UNITS
  - LOT SIZE/ANNUAL RATE COST EFFECTS
  - OPTIMUM QUANTITY PER YEAR
- LOW VOLUME PRODUCTION COST DATA (FOR REUSABLE ENGINES)
  - THEORETICAL FIRST UNIT COST
  - COST IMPROVEMENT SLOPE
  - CUMULATIVE AVERAGE COST FOR 50, 300, and 1000 UNITS
  - LOT SIZE/ANNUAL RATE COST EFFECTS
  - OPTIMUM QUANTITY PER YEAR
- TOOLING COSTS
  - NON-RECURRING
  - RECURRING
- PROCESS DEVELOPMENT COSTS (IF ANY)
- EQUIPMENT/FACILITY COSTS (IF ANY)
- PRODUCTION QUANTITY/RATE WHERE MANUFACTURING PROCESS CHANGES OCCUR
- OTHER RELATED INFORMATION

OXYGEN TURBOPUMP COST MODEL

MANUFACTURING SUPPORT

- DEVELOP OPERATIONAL TURBOPUMP MANUFACTURING PLAN
  - MAKE/BUY PLANS
  - MANUFACTURING PROCESS DEFINITION
  - INSPECTION, ASSEMBLY AND TEST REQUIREMENTS
  - TOOLING REQUIREMENTS
  - PROCESS DEVELOPMENT NEEDED
- USE MANUFACTURING DATA BASE TO ESTIMATE COSTS FOR "MAKE" PARTS
- WORK WITH SUPPLIERS TO OBTAIN COST ESTIMATES FOR "BUY" PARTS

OXYGEN TURBOPUMP COST MODEL

OPERATIONS COST CALCULATIONS

- MAINTENANCE COSTS GENERATED USING EXPENDABLE/REUSABLE MAINTENANCE COST SUBROUTINES

- FLIGHT SCHEDULE/BUILDUP SUBROUTINE TRACKS MISSIONS FLOWN BY EACH ENGINE SO FLEET COSTS CAN BE ACCUMULATED

- FLEET RELIABILITY VALUES CALCULATED

- ALL OPERATIONS COST ELEMENTS DEFINED

- USER CAN VARY FLIGHT SCHEDULE AND SPECIFY WHETHER ENGINES ARE EXPENDED OR REUSED

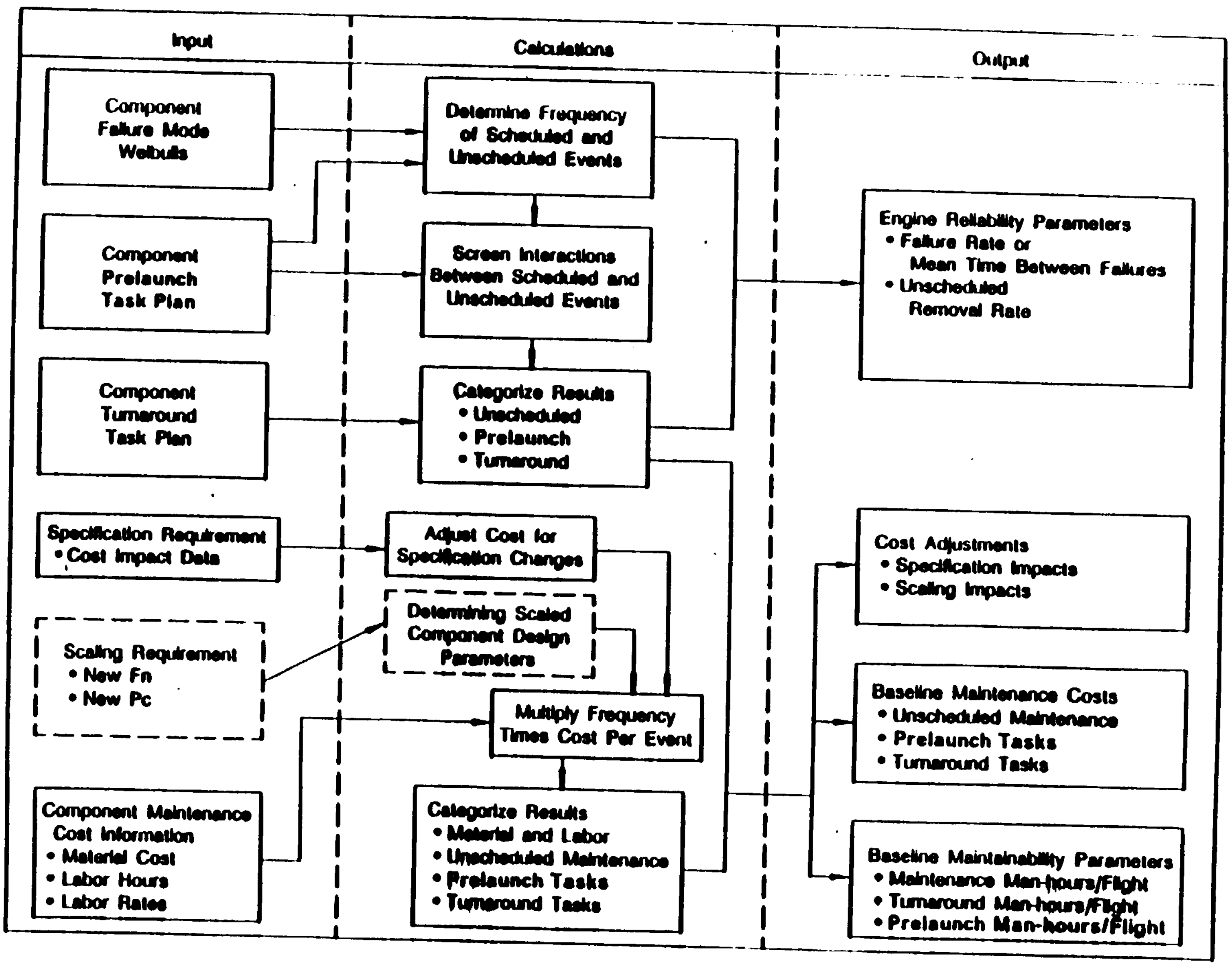
OXYGEN TURBOPUMP COST MODEL

MAINTENANCE COST SUBROUTINES

- UNSCHEDULED EVENTS DEFINED USING WEIBULLS FOR EACH FAILURE MODE
- ROUTINE SCHEDULED EVENTS DEFINED FROM RECOVERY, REFURBISHMENT, AND PRELAUNCH PLANS
- COSTS CALCULATED USING LABOR HOURS AND MATERIAL COSTS PER EVENT
- DETERMINISTIC APPROACH (WEIBULL RENEWAL THEORY) USED FOR UNSCHEDULED CALCULATIONS (REDUCES COMPUTER TIME)
- SIMILAR APPROACH USED FOR GAS TURBINE ENGINES

O.. /GEN TURBOPUMP COST MUDEL

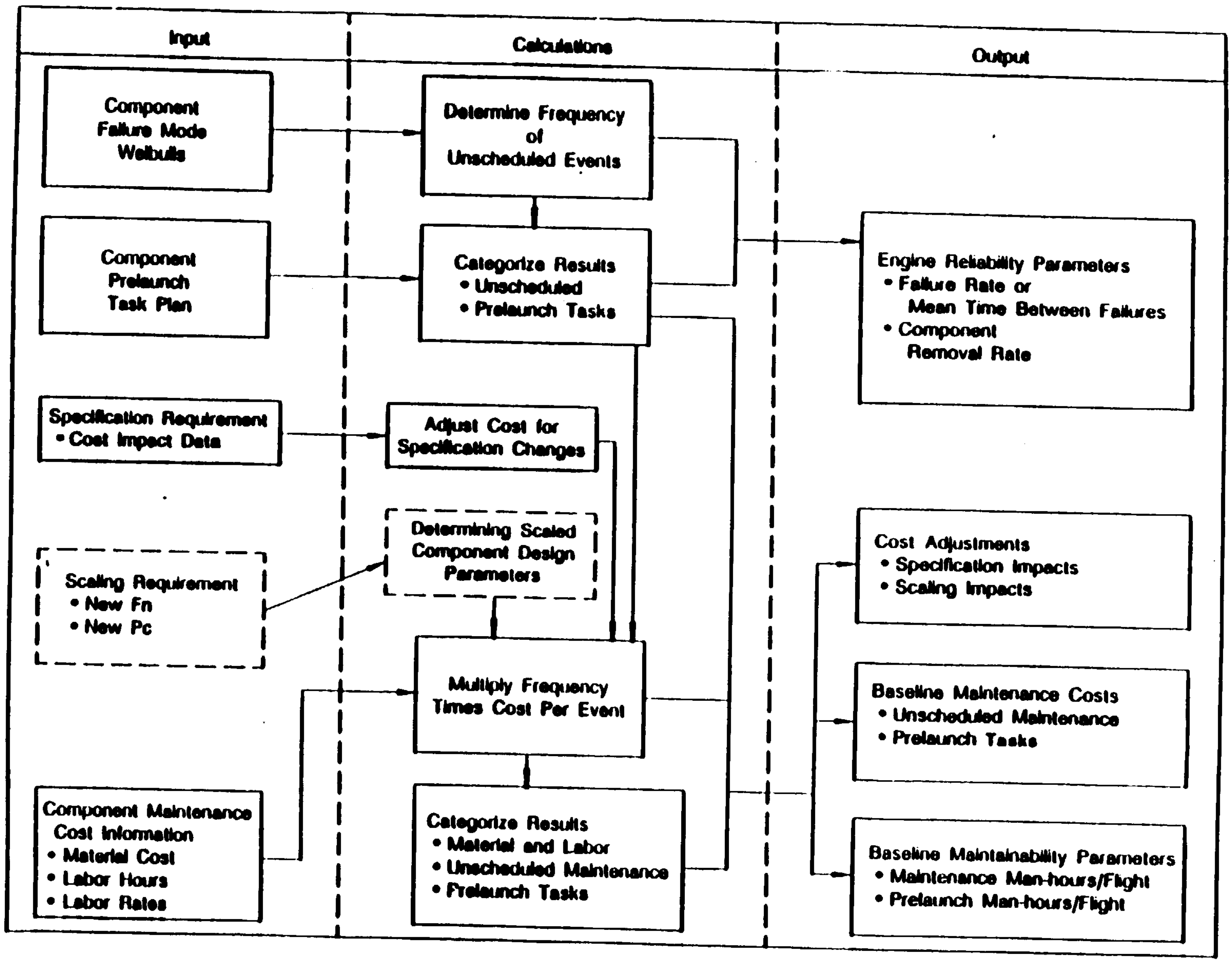
REUSABLE ENGINE MAINTENANCE COST SUBROUTINE



ORIGINAL PAGE IS
OF POOR QUALITY

OXYGEN TURBOPUMP COST MODEL

EXPENDABLE ENGINE MAINTENANCE COST SUBROUTINE



OXYGEN TURBOPUMP COST MODEL

OPERATIONS COST INPUTS

USER VARIABLES	P&W PROVIDED DATA SETS
EXPENDABLE OR REUSABLE ENGINE	EXPENDABLE/REUSABLE MAINTENANCE DATA • FAILURE MODES • WEIBULL CHARACTERISTICS • RECOVERY TASKS • REFURBISHMENT TASKS • PRELAUNCH TASKS • MAINTENANCE COST DATA FOR EACH EVENT*
MISSION FLIGHT SCHEDULE	
NO. ENGINE/VEHICLE	
THRUST LEVEL CHAMBER PRESSURE	OTHER OPERATIONS DATA • PROGRAM MANAGEMENT • SYSTEM ENGR AND INTEGRATION • FACILITIES MAINTENANCE • TRAINING • OTHER OPERATIONS AND SUPPORT • OTHER ITEMS (IF APPROPRIATE)
ALS SPECIFICATIONS ELIMINATED	
ESCALATION FACTOR(S)	

OXYGEN TURBOPUMP COST MODEL

OPERATIONS COST OUTPUT DATA

BASELINE/SCALED R&M SUMMARY*

- FAILURE RATE OR MTBF
- UNSCHEDULED REMOVAL RATE
- UNSCHEDULED MAINTENANCE MH/FLIGHT
- ROUTINE SCHEDULED REFURBISHMENT MH/FLIGHT
- PRELAUNCH MH/FLIGHT
- RECOVERY MH/FLIGHT
- SPECIFICATION IMPACTS

BASELINE/SCALED MAINTENANCE MATERIAL/LABOR COST SUMMARY*

- UNSCHEDULED MAINTENANCE COSTS
- ROUTINE SCHEDULED REFURBISHMENT COSTS
- PRELAUNCH COSTS
- RECOVERY COSTS
- SPECIFICATION IMPACTS

BASELINE/SCALED OTHER OPERATIONS COST SUMMARY*

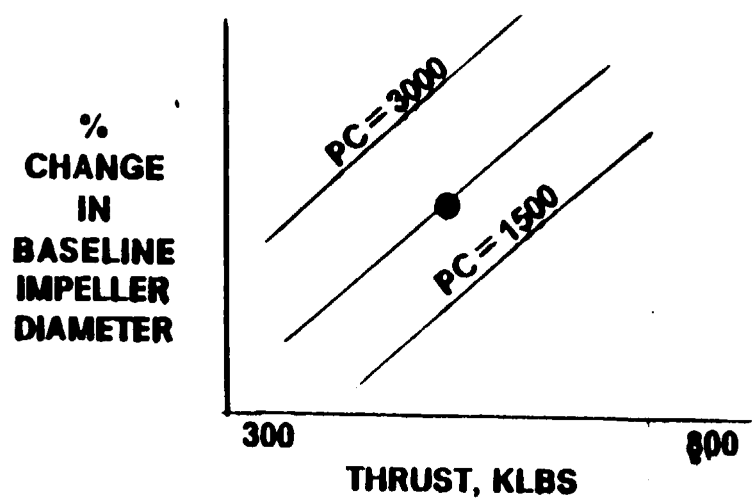
- PROGRAM MANAGEMENT
- SYSTEM ENGR AND INTEGRATION
- FACILITIES MAINTENANCE
- TRAINING
- OTHER OPERATIONS AND SUPPORT
- OTHER ITEMS (IF APPLICABLE)

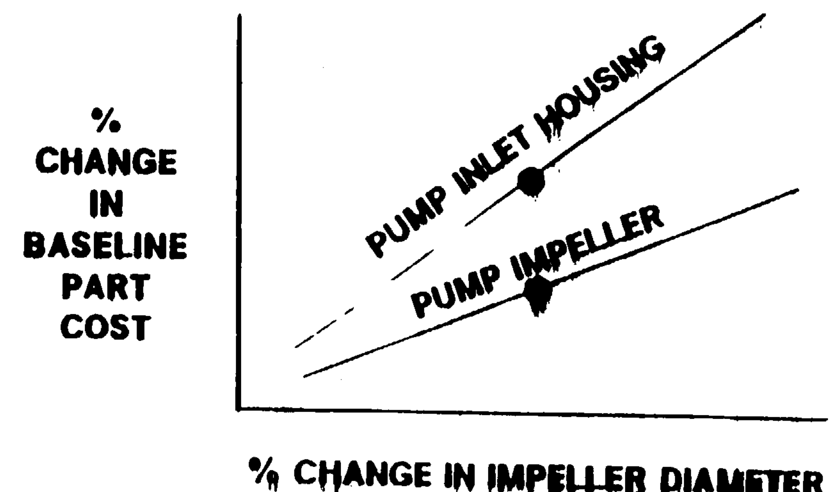
* TOTAL AND ANNUAL VALUES

OXYGEN TURBOPUMP COST MODEL

THRUST AND CHAMBER PRESSURE SCALING

- NEW THRUST AND/OR CHAMBER PRESSURE INPUT
- SCALED COMPONENT DESIGN PARAMETERS DETERMINED
- SCALED DESIGN PARAMETERS COMPARED WITH BASELINE
- PART/SUBASSEMBLY COSTS ADJUSTED USING CHANGE IN DESIGN PARAMETERS
- MATERIAL/FABRICATION/DESIGN CHANGES CONSIDERED





OXYGEN TURBOPUMP COST MODEL

GOVERNMENT SPECIFICATION COST IMPACTS

EVALUATION APPROACH

- ALL PERTINENT GOVERNMENT SPECIFICATIONS CONSIDERED
- SPECIFICATION INTENT AND POTENTIAL COST SAVINGS DETERMINED
- ALTERNATE APPROACHES THAT WILL SATISFY INTENT AND REDUCE COSTS IDENTIFIED
- RELIABILITY IMPACTS EVALUATED
- BEST ALTERNATE APPROACHES RECOMMENDED FOR TO NASA

COST MODEL

- COST IMPACT DATA SET GENERATED
- USER SPECIFIES SPECIFICATIONS TO BE EVALUATED
- MODEL PROVIDES COST IMPACTS ON BASELINE/SCALED TURBOPUMP
- BASELINE COSTS REFLECT ALTERNATE APPROACHES INCORPORATED

OXYGEN TURBOPUMP COST MODEL

MODEL VALIDATION PLAN

- COST MODEL UPDATED BEFORE DELIVERY TO REFLECT FULL-SCALE FABRICATION AND TEST EXPERIENCE

- MANUFACTURING INPUT DATA MODIFIED TO REFLECT FABRICATION DATA
  - P&W PARTS
  - VENDOR PARTS
  - ASSEMBLY
  - CALIBRATION/PROOF TESTS
  - OPERATIONAL COMPONENTS IN PRODUCTION ENVIRONMENT

- OPERATIONS INPUT DATA MODIFIED TO REFLECT TEST DATA
  - FAILURE MODES AND WEIBULLS
  - REFURBISHMENT REQUIREMENTS
  - PRELAUNCH TASKS

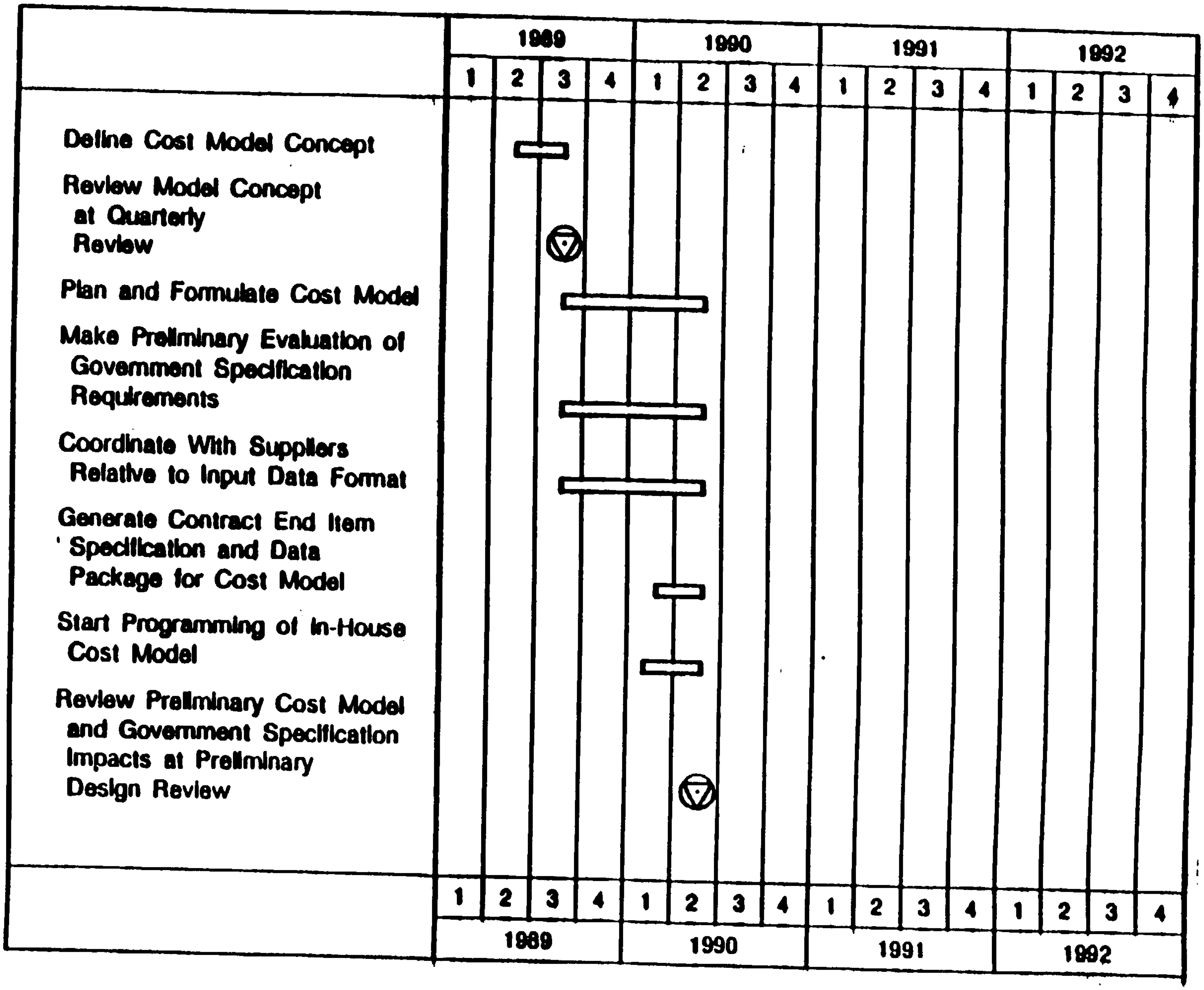
OXYGEN TURBOPUMP COST MODEL

DELIVERABLE MODEL

- MODEL AND FINAL CEI SPECIFICATION DELIVERED TO GOV'T IN SEPTEMER 1989
- USER'S MANUAL, SOURCE CODE, AND SUBSTANTIATING DATA INCLUDED
- INDEPENDENT COST ASSESSMENT DATA PROVIDED
- MODEL WRITTEN IN FORTRAN 77 OR EQUIVALENT AS AGREED TO BY NASA
- MODEL PREPARED FOR IBM PC

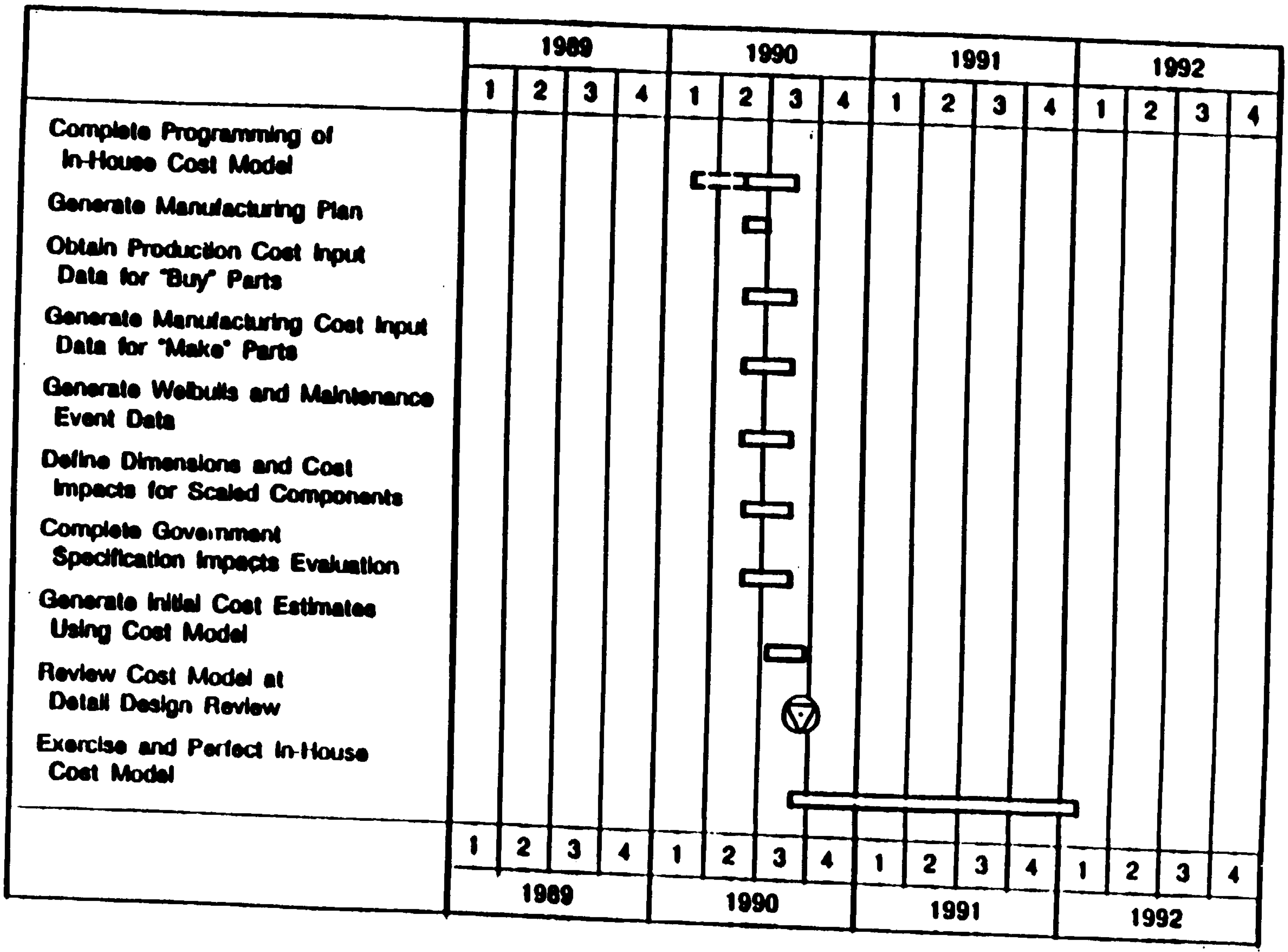
OXYGEN TURBOPUMP COST MODEL

PRELIMINARY COST MODEL SCHEDULE - BASIC PHASE



OXYGEN TURBOPUMP COST MODEL

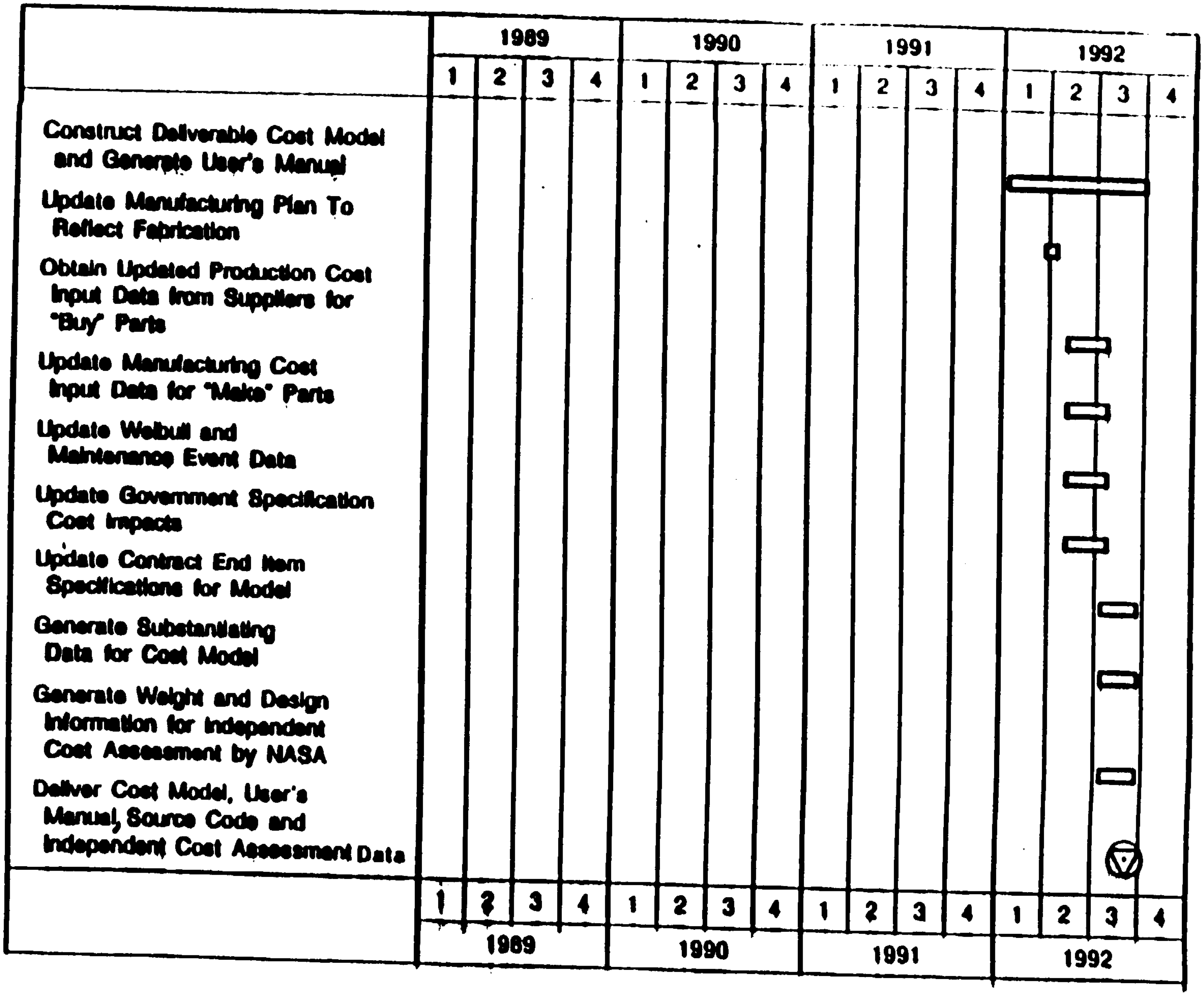
DETAILED COST MODEL SCHEDULE - OPTION PHASE



ORIGINAL PAGE IS OF POOR QUALITY

OXYGEN TURBOPUMP COST MODEL

DETAILED COST MODEL SCHEDULE - OPTION PHASE (CONTINUED)



OXYGEN TURBOPUMP COST MODEL

NASA REQUIREMENTS

- NASA WORKING COMPATIBILITY ISSUES
- PRELIMINARY MODEL REQUIREMENTS DISTRIBUTED
- P&W COMMENTS SUBMITTED
- NASA PREPARING FINAL REQUIREMENTS

BOOSTER/ORBITER PROPULSION
RECORD OF IMPORTANT CUSTOMER COMMUNICATIONS

CONTACT: Mr. David Taylor

P&W CONTACT: Mr. Tom Mayes

AFFILIATION: NASA/MSFC

EXTENSION: 407-796-3615

PHONE NUMBER: 205-544-0597

DATE: 8/4/89 **TIME:** 9:30am

SUBJECT: Advanced Development Program (ADP) - Cost Model Requirements

SUMMARY OF IMPORTANT INFORMATION:

Ref: Letter from Dave Taylor to Tom Mayes,
Subject same as above, dated July 19, 1989

Pratt and Whitney has reviewed the preliminary list of requirements for the cost model inputs, outputs and ground rules. We have the following comments and questions about the model requirements.

1. Shouldn't the costs be presented in constant 1987 dollars rather than constant 1989 dollars? The ALS Cost Reporting Document specifies that ALS costs be reported in 1987 dollars and as far as we know this requirement still exists.

2. Recommend that a ground rule be included regarding how acceptance test costs are to be handled for the components. Since a production component would normally be tested as part of an engine acceptance test we suggest that acceptance test costs not be included at the component level.

3. The model outputs included in this document are quite limited. Are these outputs intended to be the ones available in the ADP component cost models provided to the other engine contractors? If so, does NASA want more cost visibility from the model than this list indicates?

OXYGEN TURBOPUMP COST MODEL

COST MODEL ISSUES AND QUESTIONS

- COMPATIBILITY WITH PHASE B ENGINE COST MODELS
  - INPUT AND OUTPUT FORMAT
  - PROGRAMMING LANGUAGE
  - COMPUTER SYSTEM
- STANDARDIZED COST GROUND RULES
  - GOVERNMENT SUPPORT COSTS
  - PERSONNEL TO BE INCLUDED IN ENGINE OPERATIONS COSTS
  - COSTS OF ENGINE CAUSED LAUNCH DELAYS
  - COMPONENT ACCEPTANCE TEST COSTS
- STANDARDIZED INPUT AND OUTPUT
  - NON-RECURRING PRODUCTION COSTS
  - GOV'T SPECIFICATION COST IMPACTS
  - COMPONENT SCALING
  - PROGRAMMATIC COSTS (LOT, FLEET, ANNUAL, ETC)
- COST OF UNRELIABILITY
- MODEL DELIVERIES

2.4 INCONEL 718 IMPELLER CASTING DEMONSTRATION

A low cost fine grain Inconel 718 impeller was developed as part of this ADP. This task involved the successful development and demonstration of a shrouded cast impeller, metallurgical evaluation of specimens machined from the impeller, final machining and spin testing of an impeller. The impeller was balanced, assembled to an arbor, instrumented with strain gages and successfully spun to a speed that corresponded to 150% of its operating design .stress levels. This section contains objectives, work description and the accomplishments of the impeller demonstration as well as photographs of the impellers and part of the special test equipment developed for the spin test.

OXYGEN TURBOPUMP

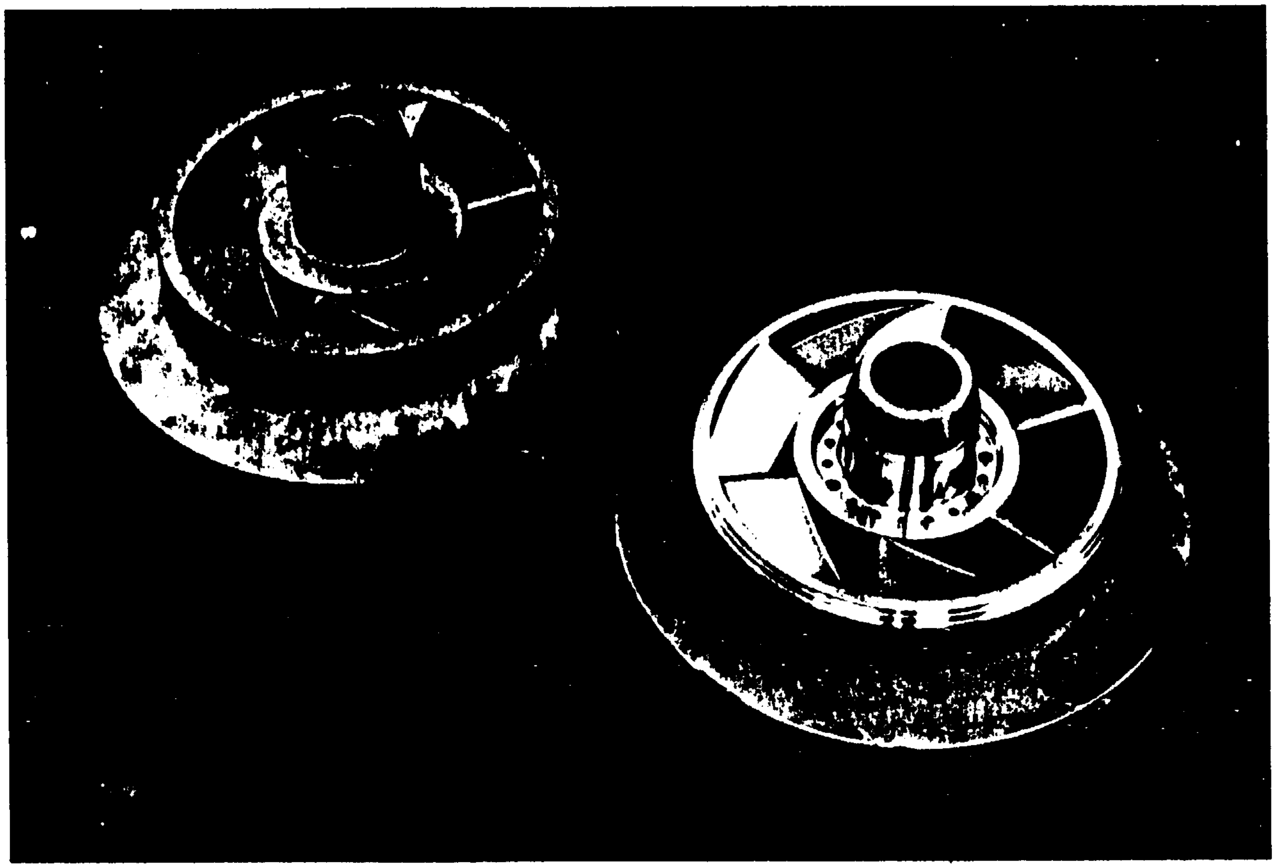
Impeller Casting Demonstration, Spin Testing and Material Characterization

- **Objective**
  - Develop low cost fine grain Inconel 718 material impellers for liquid oxygen turbopumps
- **Work Description**
  - Included the procurement of fine grain cast impellers, metallurgical evaluation of the parts, and impeller machining for a spin test. Spin test included balance, assembly to arbor, strain gage, spin, and data analysis
- **Significant Accomplishments**
  - Detailed drawings and structural analysis of test impeller completed
  - Produced several cast impellers in development demonstration
  - Produced spin test cast impeller
  - Successfully spin tested cast impeller to 150% stress level

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

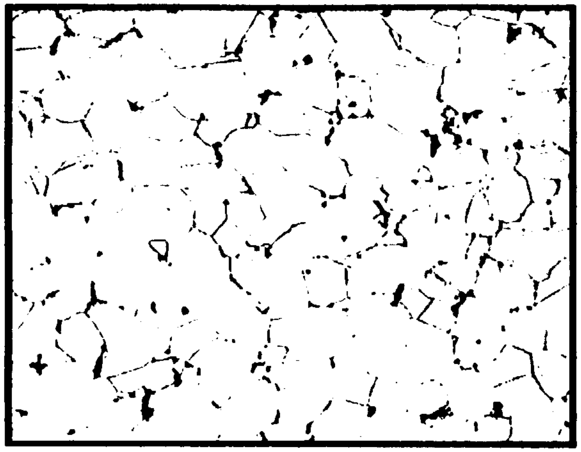
A PROTOTYPE MACHINED CAST IMPELLER, USED FOR SPIN TEST EVALUATION, IS SHOWN COMPARED TO AN AS-CAST IMPELLER



FE 623677

OXYGEN TURBOPUMP

Comparative Grain Size - 100X Magnification



Demonstration sample
ASTM 3

Production housing
ASTM 2-3

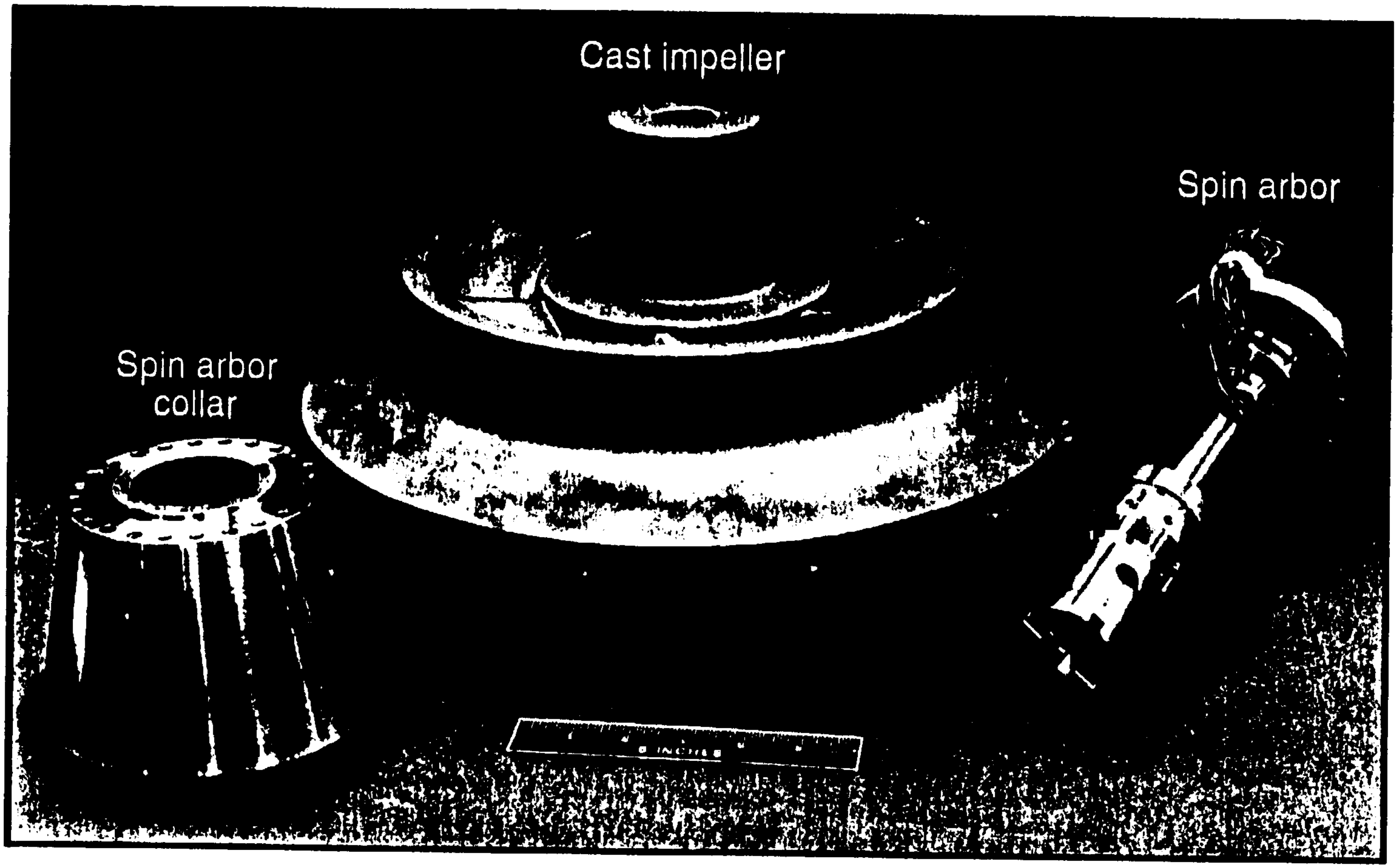
Spin impeller
ASTM 1

36173

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

THE SPIN TEST DEMONSTRATED THE STRUCTURAL INTEGRITY AND VERIFIED PREDICTED STRESSES IN THE DESIGN MODEL



FE621520

36172

2.5 DISK / SHAFT FORGING DEMONSTRATION

A demonstration of a single piece forged liquid oxygen turbopump disk / shaft was an objective of this ADP. As part of that task, one piece disk / shaft components were successfully forged from A286 and Waspaloy materials. Each of these forgings was evaluated for metallurgical and material properties and demonstrated uniform grain size throughout this large forging, a requirement for providing adequate strength.

This section contains the objectives, work description and accomplishments of the forging demonstration as well as a photograph of a forged one piece disk / shaft.

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

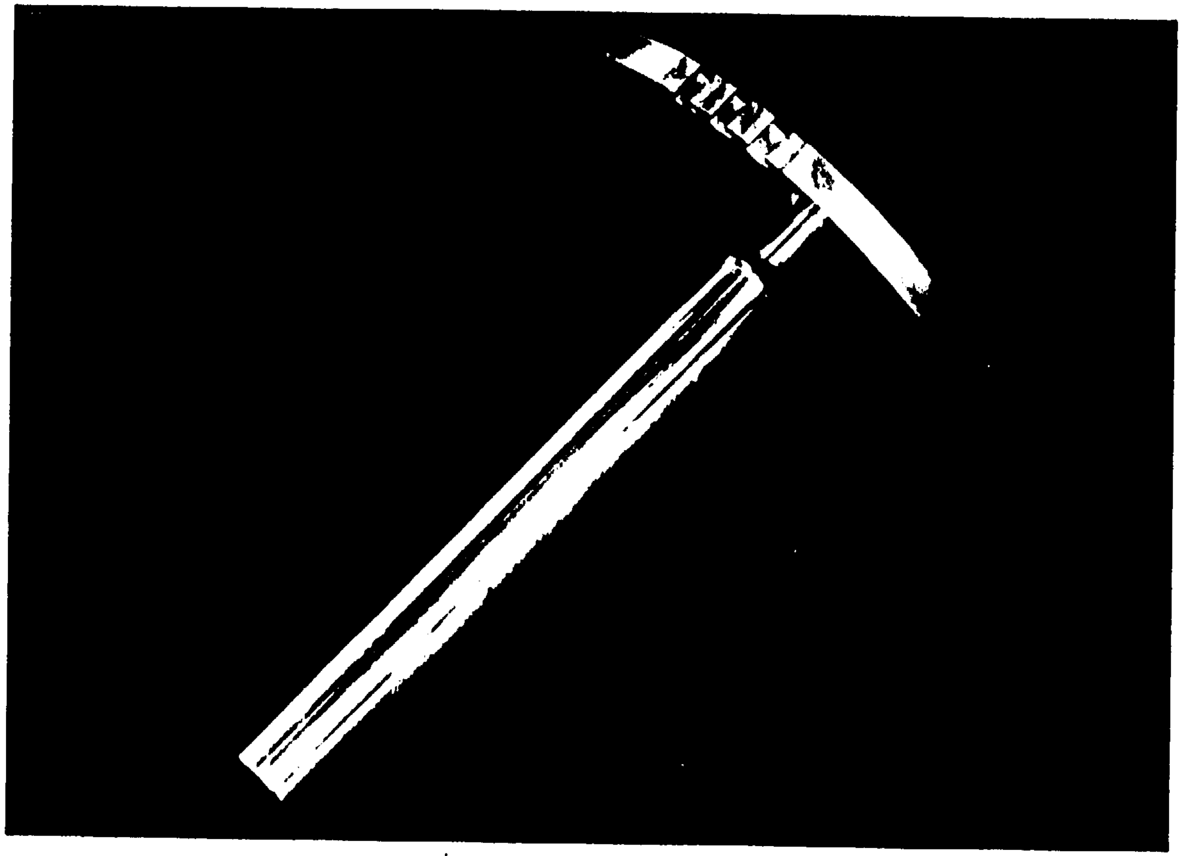
Disk / Shaft Demonstration and Material Characterization

- **Objective**
  - Develop and demonstrate materials and processes required for fabrication of the liquid oxygen turbopump one piece disk / shaft.
- **Work Description**
  - Included the procurement of A286 and Waspaloy one-piece disk / shaft components, material testing and evaluation to determine if mechanical requirements are met.
- **Significant Accomplishments**
  - Demonstrated forged alloy shaft for disk / shaft in Waspaloy and A286.
    - Evaluated forgings for metallurgical and material property acceptability.
  - Currently demonstrating high strength Waspaloy in 650K configuration.
    - Subscale program identified process parameters and forging technique.
    - Full scale demonstration will provide prototype disk / shaft for evaluation.

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

THE CAPABILITY OF FORGING A ONE-PIECE DISK/SHAFT FOR THE STME OXYGEN TURBOPUMP WAS DEMONSTRATED. THE ONE PIECE DESIGN IS LOWER COST THAN A TWO PIECE ASSEMBLY



FE623679

36169

2.6 CASTING DEMONSTRATION OF STRUCTURAL HOUSING AND MATERIAL CHARACTERIZATION

One of the objectives of this ADP was to select the lowest cost alloy and fabrication process for the hardware, while ensuring high reliability. The liquid oxygen turbopump design at PDR contained five structural housings; two large turbine housings that serve as inlet and exit volutes for the gas generator working fluid, two pump housings, an inlet and a volute discharge housing, and an outer case housing.

Under this task, casting demonstrations, material screening and characterization of specific materials were initiated to determine which of the cast materials could meet the structural requirements of the pump and turbine. Full size hardware was cast using SSME-ATD tooling that was representative of this program from the standpoint of hardware size. Materials demonstrated included fine grain Inconel 718 (PWA-1490) and fine grain Haynes 230. The demonstrations were successful, as fine grain resulted in the materials cast. The housing materials were subjected to mechanical testing, including low cycle fatigue, high cycle fatigue, creep, crack propagation and toughness. Haynes 230 material was not selected because it lacked sufficient strength for this application. Since PWA-1490 was selected as the structural housing material, a full characterization of the material in hydrogen was conducted.

This section contains the objectives, work description and accomplishments of this task as well as photographs of the cast housing, test specimens and grain sizes. Report FR-22579, a summary report of PWA 1490 material characterization, is also included.

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

Casting Demonstration of Structural Housing and Material Characterization

- **Objective**
  - Develop and demonstrate materials and processes required for fabrication of the liquid oxygen turbopump castings.
- **Work Description**
  - Included the procurement of Inconel 718 fine grain housing, specimen machining, mechanical testing (smooth, notched tensile, LCF, HCF, creep, crack prop., fracture toughness etc...) and generation of design curves.
- **Significant Accomplishments**
  - Successfully cast alloys in full size structural configurations
  - Characterization of structural housing fine grain Inconel 718 (PWA 1490) in H2 is complete.
  - Have completed the planned 134 point PWA 1490 test matrix. Found reduction of properties only during LCF testing in 1000 PSI, ambient temperature, H2 environment.

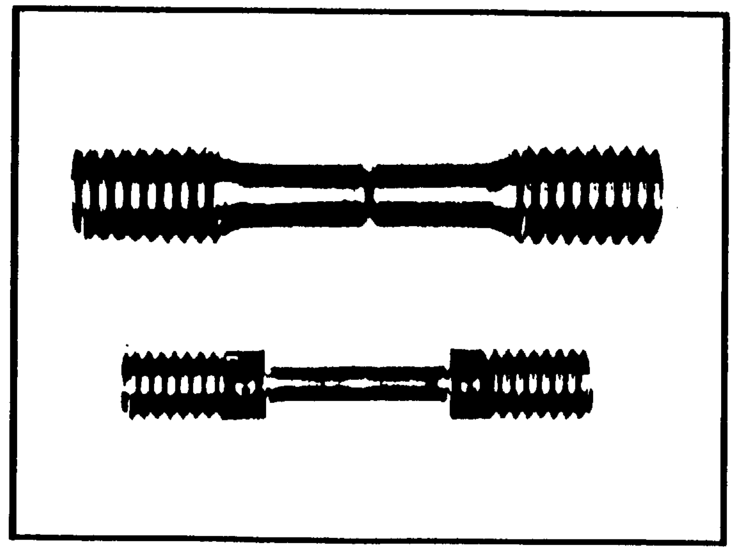
SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

MATERIAL SPECIMENS MACHINED FROM CAST HOUSINGS WERE USED FOR CHARACTERIZATION OF FINE GRAIN INCONEL 718 MATERIAL (PWA 1490) IN A SIMULATED TURBINE OPERATING ENVIRONMENT

FE 603404

Inconel 718 cast housing



AVL372401

Test specimens

36171

FR-22579
15 December 1992

NATIONAL LAUNCH SYSTEM ADVANCED DEVELOPMENT OXIDIZER TURBOPUMP PROGRAM

SUMMARY REPORT

Material Characterization of Fine-Grain Cast Inconel 718 (PWA1490) for Turbine Structural Housing Applications in the NLS Oxidizer Turbopump

Prepared Under Contract Number
NAS8–37595
DRL Sequence No. 03

Prepared for
George C. Marshall Space Flight Center
National Aeronautics and Space Adminstration

Prepared by
United Technologies Corporation
Pratt & Whitney
Government Engines & Space Propulsion
West Palm Beach, Florida 33410-9600

FOREWORD

This summary report is submitted to NASA-Marshall Space Flight Center, Huntsville, Alabama by Pratt & Whitney/Government Engines & Space Propulsion. The report contains a summary of material characterization testing, completed on fine-grain cast Pratt & Whitney 1490 (Inconel 718), for turbine structural housing applications in the NLS oxidizer turbopump. The test effort was initiated in November 1990 and completed in August 1992.

TABLE OF CONTENTS

RELIABILITY CENTERED MAINTENANCE ANALYSIS UPDATE REPORT

PRECEDING PAGE BLANK NOT FILMED

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION 1.0
INTRODUCTION

Pratt & Whitney (P&W), under the National Launch System (NLS) Advanced Development Oxidizer Turbopump Program (NAS8–37595), has been conducting ongoing fabrication demonstrations and material evaluation tasks to support the selection of baseline materials for various oxidizer turbopump (OTP) components. This task complements the trade studies and OTP preliminary design efforts being conducted under Phase B of the Space Transportation Engine Program (NAS8–38170). The objective of these combined studies is to select the lowest-cost alloy and fabrication process for OTP components, while providing adequate structural integrity.

At the inception of this program, material evaluation efforts began for the turbine structural housings. The OTP uses two large turbine housings that serve as inlet and exit volutes for the gas generator working fluid. Considerable benefits in cost and lead time could be attained through the use of cast housings, although a suitable cast alloy would be required to meet the structural demands of the turbine operating environment.

Material screening and characterization of fine-grain cast PWA 1490 (Inconel 718) and other potential cast alloys were initiated to determine which cast material (if any) could meet the structural requirements of the turbine. Based on the material property data generated and input from casting suppliers, fine-grain cast PWA 1490 was selected as the optimum alloy for the turbine structural housings. Full characterization of this alloy was continued to obtain the data required for design. This report contains the results of all material testing completed on PWA 1490 during this advanced development program.

1.1 PWA 1490 BACKGROUND

The PWA 1490 used in the characterization program was machined from structural housings that were cast using the Microcast-X (MX) process. The MX process, developed by the Howmet Corporation, is a proprietary fine-grain casting process that has been successfully used to cast many large structural components with a grain size ranging between ASTM 1.5 and 5. The process produces a cellular-like microstructure rather than the dendritic structure normally observed in cast alloys. These grains closely resemble the grains in a forging. A fine-grain, cellular-like microstructure provides improved mechanical property uniformity, increased fatigue properties and ductility, and better weldability. These benefits are derived at the expense of high-temperature stress rupture properties, however, stress rupture is less important for this application.

Since the OTP housings will be exposed to a hydrogen environment, material resistance to hydrogen embrittlement must be determined. Therefore, PWA 1490 and the other potential alloys were tested in 1000 psi hydrogen for comparison with standard air tests. Extensive mechanical property testing detailed in the body of this report shows that PWA 1490 has excellent resistance to hydrogen embrittlement at pressures under 1000 psi. The testing also demonstrated that PWA 1490 outperformed the other potential alloys.

SECTION 2.0
PWA 1490 MATERIAL CHARACTERIZATION RESULTS

2.1 SUMMARY MATRIX

A summary of the characterization testing performed on PWA 1490 is provided in Table 2-1. This material property testing was initiated in November 1990 and completed in August 1992.

Table 2-1. PWA 1490 Characterization Matrix Completed

Test Type	*Temperature C° (°F)*	*Gas Environment*	*No. Tests Required*	*No. Tests Completed*
Smooth Tensile	RT	Air	10	8 (2*)
	RT	Hydrogen - 1000 psi	13	14
	537.8 (1000)	Air	3	8
	537.8 (1000)	Hydrogen - 1000 psi	6	10
Notch Tensile	RT	Air	10	7 (3*)
	RT	Hydrogen - 1000 psi	10	10
	537.8 (1000)	Air	3	7
	537.8 (1000)	Hydrogen - 1000 psi	3	9
Smooth LCF	RT	Air	6	6
	RT	Hydrogen - 1000 psi	6	7
	537.8 (1000)	Air	4	4
	537.8 (1000)	Hydrogen - 1000 psi	6	6
Double Notch LCF	RT	Air	9	5 (4*)
	RT	Hydrogen - 1000 psi	5	5
	537.8 (1000)	Air	5	6
	537.8 (1000)	Hydrogen - 1000 psi	5	5
Smooth HCF	RT	Air	9	6 (3*)
	RT	Hydrogen - 1000 psi	6	6
	537.8 (1000)	Air	5	5
	537.8 (1000)	Hydrogen - 1000 psi	5	8
Crack Propagation	RT	Air	2	(2*)
	RT	Hydrogen - 1000 psi	2	2
Fracture Toughness	RT	Hydrogen - 1000 psi	1	1
		Total:	134	159

* Indicates Tests Completed Under Different Contract

2.2 SMOOTH TENSILE TESTS

Strength and ductility of PWA 1490 was characterized in air and 1000 psig hydrogen at both room temperature and 537.8°C (1000°F). Baseline air tensile testing was performed in a standard air environment at atmospheric pressure. Hydrogen tensile testing was performed in a 1000 psig environment with less than 1ppm oxygen. Additional tests were completed in 5000 psig to compare the hydrogen degradation of PWA 1490 tensile properties to other cast Inconel 718 test data. Also, attempts were made to maximize the hydrogen degradation of PWA 1490 by exposing specimens to a 6 hour hydrogen bath prior to test. The results of required tests and the additional tests are given in Table 2-2 and Table 2-3. Table 2-2 features all room temperature tests completed on PWA 1490, while Table 2-3 shows the results of all 537.8°C (1000°F) testing. All material used during this characterization program was machined from cast structural housings of comparable size and shape to the STME LOX turbopump turbine housings. This ensures that all resulting data is representative of actual material properties within a PWA 1490 structural housing. Cast bars or plates were not used because they yield an unrealistic optimum metallurgical state and higher than average material properties.

Table 2–2. Smooth Tensile Properties of PWA 1490 in Air and Gaseous Hydrogen at Room Temperature

Specimen Identity	Environment	Pressure (psig)	Temperature C° (°F)	Strength 0.2% Yield (KSI)	Strength Ultimate (KSI)	Ductility EL (%)	Ductility RA (%)
2899-1	Air	0	23.9 (75)	149.1	170.7	11.5	17.5
-2	Air	0	23.9 (75)	146.4	175.0	19.2	28.8
-3	Air	0	23.9 (75)	149.6	169.1	8.8	17.2
2900-7	GH_2	1000	23.9 (75)	153.3	176.3	16.0	24.8
-8	GH_2	1000	23.9 (75)	151.2	173.3	16.9	27.6
-9	GH_2	1000	23.9 (75)	150.6	173.9	15.5	21.5
3028-1*	GH_2	1000	23.9 (75)	154.6	165.5	3.5	10.9
-2*	GH_2	1000	23.9 (75)	153.2	164.2	4.8	11.4
3253-6	GH_2	5000	23.9 (75)	155.1	176.8	13.5	25.8
-7	GH_2	5000	23.9 (75)	151.5	175.8	13.3	22.6
-8	GH_2	5000	23.9 (75)	148.6	168.9	10.9	20.8
3404-1	Air	0	23.9 (75)	147.6	168.5	14.1	26.5
-2	Air	0	23.9 (75)	146.3	168.5	15.2	25.0
-3	Air	0	23.9 (75)	148.0	170.9	16.7	23.7
-4	GH_2	1000	23.9 (75)	148.6	171.4	14.9	26.1
-5	GH_2	1000	23.9 (75)	147.4	170.1	18.1	30.2
-6	GH_2	1000	23.9 (75)	148.8	172.6	18.5	28.3
-7	GH_2	5000	23.9 (75)	145.5	167.2	14.3	22.2
-8	GH_2	5000	23.9 (75)	144.8	165.2	14.7	23.3
-9	GH_2	5000	23.9 (75)	143.0	163.1	14.7	27.2
3644-1	Air	0	23.9 (75)	146.9	166.4	11.7	18.5
-2	Air	0	23.9 (75)	145.5	166.9	15.3	23.3
3645-3	GH_2	1000	23.9 (75)	150.6	166.6	6.1	8.9
-4	GH_2	1000	23.9 (75)	147.0	168.3	14.0	22.6
3849-1	GH_2	1000	23.9 (75)	149.9	174.7	19.5	29.0
-2	GH_2	1000	23.9 (75)	147.6	160.2	5.5	18.3
-3	GH_2	1000	23.9 (75)	148.8	171.2	17.6	27.8
-4	GH_2	1000	23.9 (75)	133.8	152.1	9.2	19.3

*6 Hour Exposure to 1000 psig Gaseous Hydrogen at 1000°F Prior to Test

Table 2-3. Smooth Tensile Properties of PWA 1490 in Air and Gaseous Hydrogen at 537.8°C (1000°F)

				Strength		Ductility	
Specimen Identity	Environment	Pressure (psig)	Temperature C° (° F)	0.2% Yield (ksi)	Ultimate (ksi)	EL (%)	RA (%)
2899-4	Air	0	537.8 (1000)	122.0	135.7	6.8	23.1
-5	Air	0	537.8 (1000)	121.8	140.3	16.0	31.4
-6	Air	0	537.8 (1000)	121.8	140.0	18.8	33.1
2900-10	GH_2	1000	537.8 (1000)	122.9	139.9	11.2	21.9
-11	GH_2	1000	537.8 (1000)	119.7	136.5	14.5	24.0
-12	GH_2	1000	537.8 (1000)	120.8	137.9	16.1	28.7
3028-3*	GH_2	1000	537.8 (1000)	128.1	142.5	10.5	23.0
-4*	GH_2	1000	537.8 (1000)	124.8	140.8	10.5	22.2
3253-9	GH_2	5000	537.8 (1000)	119.6	137.4	15.5	26.2
-10	GH_2	5000	537.8 (1000)	123.7	141.9	12.8	22.2
-11	GH_2	5000	537.8 (1000)	122.6	139.7	12.1	20.4
3404 -10	Air	0	537.8 (1000)	120.6	138.1	15.5	33.1
-11	Air	0	537.8 (1000)	122.1	139.9	14.9	29.8
-12	Air	0	537.8 (1000)	120.9	137.2	13.3	30.9
-13	GH_2	1000	537.8 (1000)	120.8	136.1	14.3	31.3
-14	GH_2	1000	537.8 (1000)	117.8	135.2	16.5	32.1
-15	GH_2	1000	537.8 (1000)	120.0	136.3	14.1	32.7
-16	GH_2	5000	537.8 (1000)	117.9	132.8	15.6	25.8
-17	GH_2	5000	537.8 (1000)	113.3	127.7	12.7	21.6
-18	GH_2	5000	537.8 (1000)	119.8	133.8	12.7	25.3
3644-6	Air	0	537.8 (1000)	124.1	140.7	16.5	30.5
-7**	Air	0	537.8 (1000)	94.5	118.1	27.3	38.6
3645-8	GH_2	1000	537.8 (1000)	122.4	137.5	14.8	28.4
-9	GH_2	1000	537.8 (1000)	119.7	134.1	13.1	25.5

*6 Hour Exposure to 1000 psig Gaseous Hydrogen at 1000°F Prior to Test
**Temperature Reached 1500°F Before Stabilizing at 1000°F Data Not Included in Mean

2.3 NOTCH TENSILE TESTS

Notch tensile tests were performed on PWA 1490 to determine the notch strength of the alloy in both air and 1000 psig hydrogen. Baseline air testing was completed in a standard air environment at atmospheric pressure. Hydrogen tensile testing as performed in a 1000 psig environment with less than 1 ppm oxygen. Added tests, not driven by design requirements, were completed in 5000 psig to determine the maximum degradation possible in a hydrogen environment. Hydrogen degradation of PWA 1490 properties was also tested by exposing specimens to a 6 hour hydrogen bath prior to test. The results of all the notch tensile tests are given in Table 2–4 and 2–5. All room temperature lists are shown in Table 2–4. The results of all 537.8°C (1000°F) tests are given in Table 2–5.

Table 2–4. Notched Tensile Properties of PWA 1490 in Air and Gaseous Hydrogen at Room Temperature

Specimen Identity	*Environment*	*Pressure (psig)*	*Temperature C° (° F)*	*Stress Concentration (K_t)*	*Notch Strength (ksi)*
2852-13	Air	0	23.9 (75)	3.1	237.5
-14	Air	0	23.9 (75)	3.1	242.2
-15	Air	0	23.9 (75)	3.1	238.3
2851-16	GH_2	1000	23.9 (75)	3.0	243.8
-17	GH_2	1000	23.9 (75)	3.0	246.1
-18	GH_2	1000	23.9 (75)	3.0	243.3
3050-5*	GH_2	1000	23.9 (75)	3.0	224.4
3253-1	GH_2	5000	23.9 (75)	3.1	232.1
-2	GH_2	5000	23.9 (75)	2.9	238.0
-3	GH_2	5000	23.9 (75)	2.9	227.2
3992-1	Air	0	23.9 (75)	3.1	240.9
-2	Air	0	23.9 (75)	3.1	244.5
-3	GH_2	1000	23.9 (75)	2.9	235.8
-4	GH_2	1000	23.9 (75)	3.1	238.1
-5	GH_2	5000	23.9 (75)	3.1	235.5
-6	GH_2	5000	23.9 (75)	3.1	229.5
3584-A6	GH_2	1000	23.9 (75)	7.6	252.1
-B3	GH_2	1000	23.9 (75)	7.6	248.5
-C	GH_2	1000	23.9 (75)	9.2	287.3
3585-A5	Air	0	23.9 (75)	9.2	240.1
-B	Air	0	23.9 (75)	9.2	248.7

*6 Hour Exposure to 1000 psig Gaseous Hydrogen at 1000° F Prior to Test

Table 2–5. Notched Tensile Properties of PWA 1490 in Air and Gaseous Hydrogen at 537.8°C (1000°F)

Specimen Identity	Environment	Pressure (psig)	Temperature C° (°F)	Stress Concentration (K_t)	Notch Strength (ksi)
2852-19	Air	0	537.8 (1000)	3.1	199.0
-20	Air	0	537.8 (1000)	3.1	196.0
-21	Air	0	537.8 (1000)	3.1	197.8
2851-22	GH_2	1000	537.8 (1000)	3.0	193.5
-23	GH_2	1000	537.8 (1000)	3.0	194.3
-24	GH_2	1000	537.8 (1000)	3.0	192.2
3050-6*	GH_2	1000	537.8 (1000)	3.0	191.7
3253-4	GH_2	5000	537.8 (1000)	2.9	195.0
-5	GH_2	5000	537.8 (1000)	2.9	195.4
3992-7	Air	0	537.8 (1000)	3.1	197.9
-8	Air	0	537.8 (1000)	3.1	198.3
-9	GH_2	1000	537.8 (1000)	3.1	196.4
-10	GH_2	1000	537.8 (1000)	3.1	190.3
-11	GH_2	5000	537.8 (1000)	3.1	186.6
3584-F1	GH_2	1000	537.8 (1000)	7.6	190.4
-D5	GH_2	1000	537.8 (1000)	7.6	199.0
-G1	GH_2	1000	537.8 (1000)	9.2	204.6
3585-D	Air	0	537.8 (1000)	9.2	203.0
-G1	Air	0	537.8 (1000)	9.2	204.0

*6 Hour Exposure to 1000 psig Gaseous Hydrogen at 1000°F Prior to Test

2.4 SMOOTH LOW-CYCLE FATIGUE

2.4.1 SMOOTH LCF TESTING AT ROOM TEMPERATURE

Low-cycle fatigue (LCF) testing of PWA 1490 at 26.7°C (80°F) was performed in servo-hydraulic test machines, with strain feedback control. Hydrogen testing was performed in a 1000 psig environment with less than 1 ppm oxygen. The tests were run at a strain ratio (R_ϵ) of -1.0 at a cyclic frequency of 10 cpm.

Results of the requested LCF tests are presented in Table 2–6 and in Figure 2–1. Mean curves were established using maximum likelihood techniques. Lower bound curves for this data (99 percent) were estimated in accordance to standard statistical methods.

Figure 2–1 compares the results of the room temperature LCF tests in hydrogen to baseline air data. The room temperature 1000 psi hydrogen: resulted in a 2x debit in smooth LCF life.

Table 2–6. Strain Control Fatigue Testing of PWA 1490 (Microcast Inco 718) LCF Specimens (FAT 1000), R_ϵ = -1.0, Frequency = 10 cpm

Sample Number	*Total Srain Range (%)*	*Inelastic Strain Range (%)*	*Max Stress (ksi)*	*Mean Stress (ksi)*	*Modulus (MSI)*	*Environment**	*Temp C° (° F)*	*Cycles to Failure*
B3	0.94	0.08	119.0	-2.9	29.8	GH_2	26.7 (80)	2,419
B4	0.75	< 0.01	107.0	0.0	29.4	GH_2	26.7 (80)	+3,870 **
B5	0.75	< 0.01	109.6	1.5	29.3	GH_2	26.7 (80)	5,270
B7	0.75	< 0.01	104.5	-2.9	29.5	GH_2	26.7 (80)	4,205 ***
B6	0.56	< 0.01	78.7	-1.4	28.6	GH_2	26.7 (80)	31,092
B8	0.56	< 0.01	80.3	1.4	28.6	GH_2	26.7 (80)	43,000
B7	0.38	< 0.01	56.5	2.8	28.9	GH_2	26.7 (80)	+101,400**

* GH_2 - 1000 psig Hydrogen Environment Containing Less Than 1 ppm O_2
** Test Terminated Prior to Specimen Failure, treated as a Censored Data Point in the Regression Analysis
*** Run Previously at a Lower Strain Range

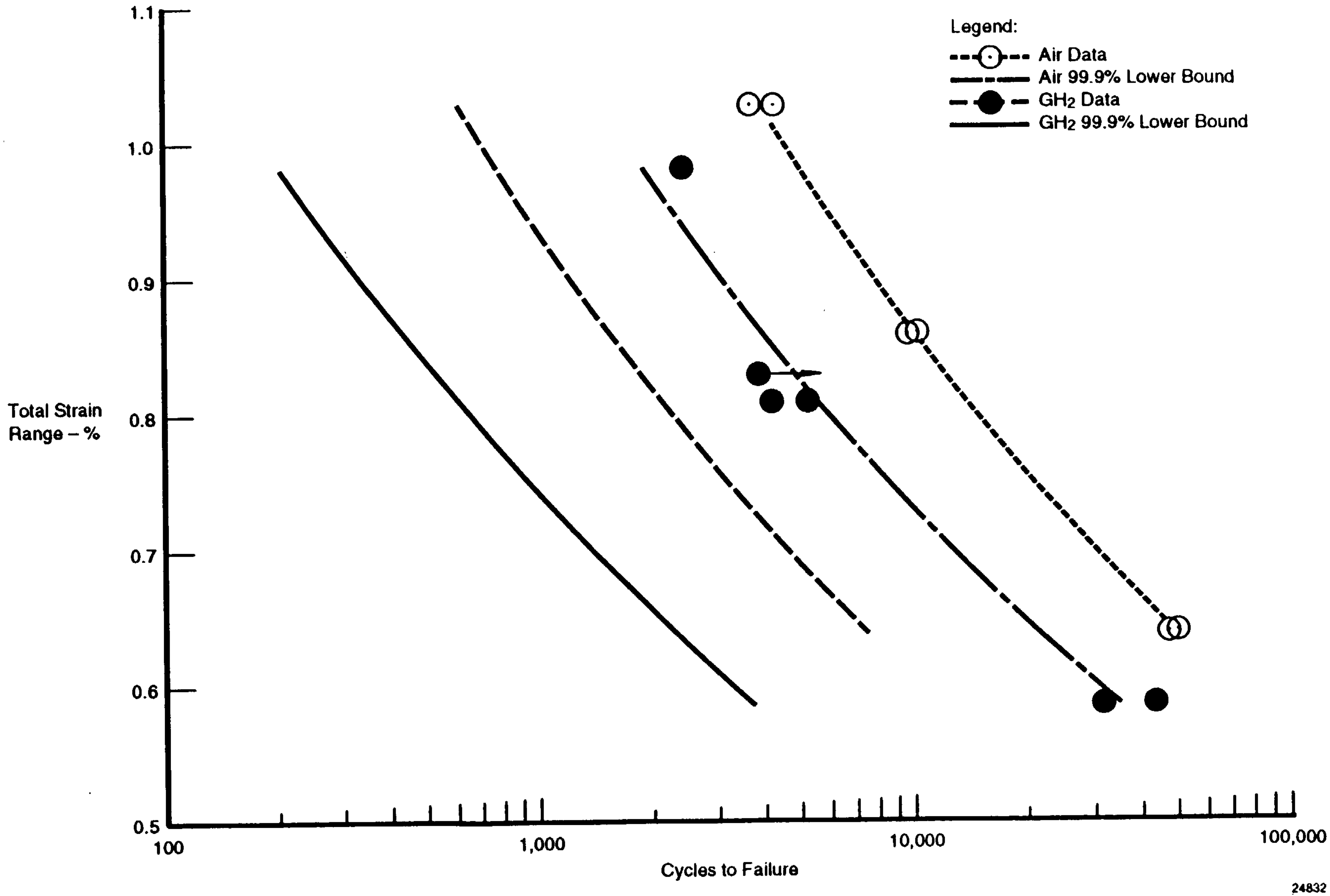


Figure 2–1. LCF Testing of PWA 1490: Strain Control Fatigue Testing of Smooth LCF Specimens (FAT 1000) Was Performed in Air and 1000 psig GH_2 at 26.7 °C (80 °F), Cyclic Frequency – 10 to 30 cpm, R_ϵ = -1.0, K_t -1.00 Conclusion: 2X Debit by 1000 psig Hydrogen at Room Temperature

2.4.2 SMOOTH LCF TESTING AT 537.8°C (1000°F)

Low-cycle fatigue (LCF) testing of PWA 1490 at 26.7°C (80°F) was performed in servo-hydraulic test machines, with strain feedback control using strain control (K_t = 1.00) LCF specimens. Baseline air testing was performed in a standard air environment at atmospheric pressure. Hydrogen testing was performed in a 1000 psig environment with less than 1 ppm oxygen. The tests were run at a strain ratio (R_ϵ) of -1.0 at cyclic frequency of 10 to 30 cpm.

Results of the requested LCF tests are presented in Table 2–7 and in Figure 2–2. Mean curves, for the air and hydrogen data, were established using maximum likelihood techniques. Lower bound curves for this data (99.9 percent) were estimated in accordance to standard statistical methods.

Two specimens failed at inclusions in the gage. These specimens are identified in Table 2–7. SEM and microprobe analysis were performed on ample number 16 to determine the composition of the inclusion. The determination was that the inclusion was alumina.

Figure 2–2 compares the results of the 537.8°C (1000°F) LCF tests in hydrogen to baseline air data. The 537.8°C (1000°F), 1000psi hydrogen caused no debit in smooth LCF life.

Table 2–7. Strain Control Fatigue Testing of PWA 1490 (Microcast Inco 718) LCF Specimens (FAT 27300, FAT 10000), R_ϵ = -1.0, Frequency = 10 to 30 cpm

Sample Number	*Total Srain Range (%)*	*Inelastic Strain Range (%)*	*Total Stress Range (ksi)*	*Mean Stress (ksi)*	*Modulus (MSI)*	*Environment **	*Temp C° (°F)*	*Cycles to Failure*
13	1.2	0.39	189.6	-2.1	23.7	Air	537.8 (1000)	1,801
14	0.8	0.13	169.2	-0.5	24.2	Air	537.8 (1000)	4,800
18	0.5	<0.01	122.0	-3.0	24.0	Air	537.8 (1000)	+268,000
16	0.5	<0.01	119.1	2.0	24.1	Air	537.8 (1000)	23,262 **
22	1.13	0.24	205.4	-3.5	24.3	GH_2	537.8 (1000)	1,823
20	1.13	0.20	209.9	-3.6	24.7	GH_2	537.8 (1000)	1,815
23	0.75	0.06	173.8	0.0	24.6	GH_2	537.8 (1000)	9,404
19	0.75	0.04	177.4	-1.4	25.3	GH_2	537.8 (1000)	9,612
18 ****	0.80	_ · _ _	169.2	-0.5	_ · _ _	GH_2	537.8 (1000)	3,908 ***
21	0.47	<0.01	116.9	2.2	25.3	GH_2	537.8 (1000)	95,594

*Air - Standard Air Environment, Atmospheric Pressure
GH_2 - 1000 psig Hydrogen Environment Containing Less Than 1 ppm O_2
**Test Terminated Prior to Specimen Failure, Treated as a Failure in the Regression Analysis
***Failure Originated at an Inclusion
****Smooth LCF Specimen (FAT 27300, With no Collars) Run in Hydrogen Under Load Control

master

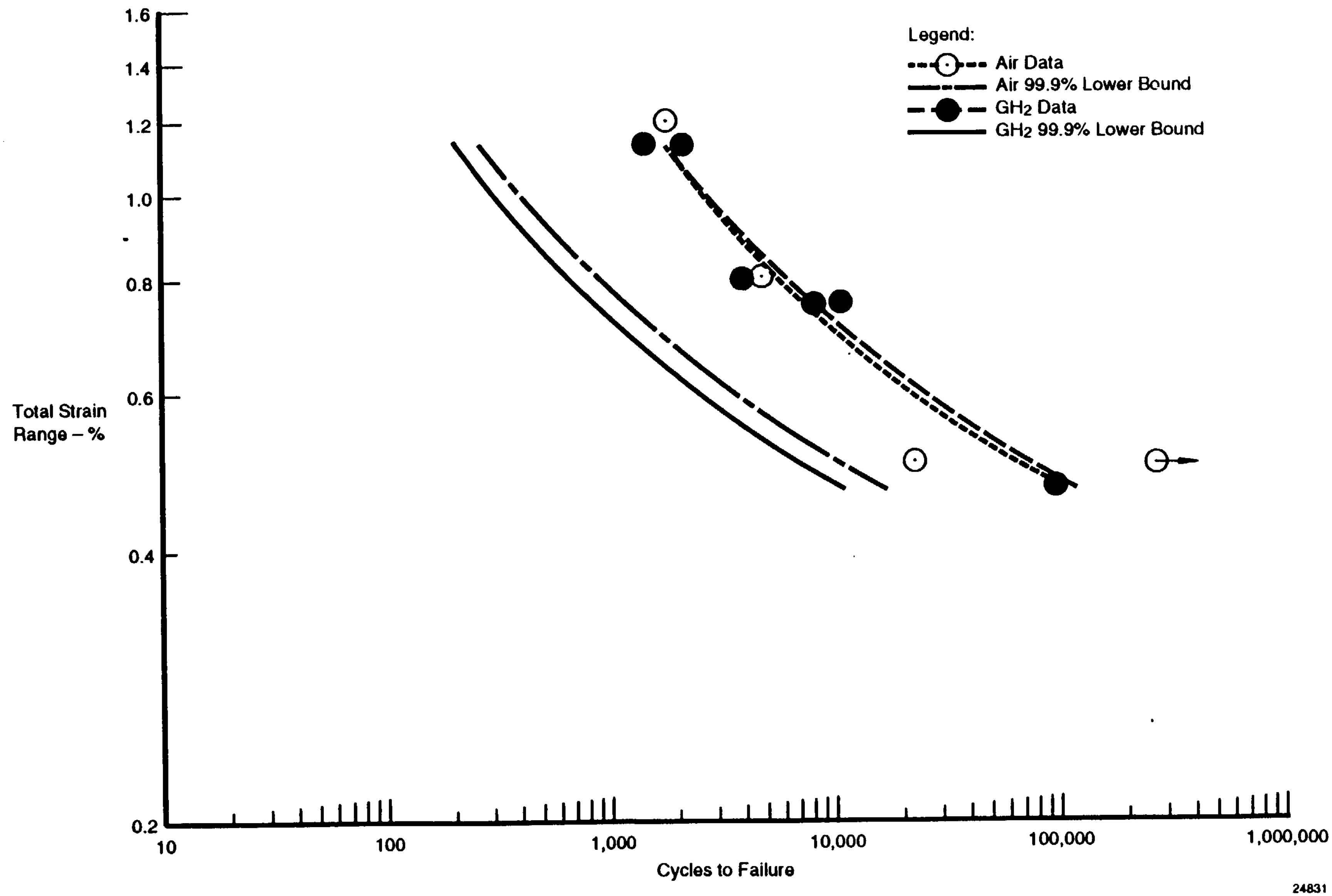


Figure 2–2. LCF Testing of PWA 1490: Strain Control Fatigue Testing of Smooth LCF Specimens (FAT 27300/1000) Was Performed in Standard Air Environment and 1000 psig GH_2 at 537.8°C (1000°F), Cyclic Frequency – 10 to 30 cpm, R_ϵ = -1.0, K_t -1.00 Conclusion: No Significant Debit by 1000 psig Hydrogen at 537.8°C (1000°F)

2.5 DOUBLE NOTCH LCF

2.5.1 DOUBLE NOTCH LCF AT ROOM TEMPERATURE

Low-cycle fatigue (LCF) testing of PWA 1490 at 26.7 °C (80 °F) was performed in servo-hydraulic test machines, with load feedback control, using double notched (K_t = 2.18) LCF specimens. Baseline air testing was performed in a standard air environment at atmospheric pressure and given in graphical form only.

The data is presented in Table 2–8 and in Figure 2–3. Specimens were tested at room temperature in 1000 psig hydrogen. The tests were run to failure at a stress ratio (R_σ) of and 0.05 (all tensile stress cycle) at a cyclic frequency of 10 cpm. Figure 2–3 shows a comparison between the hydrogen and air data.

Mean curves were established using maximum likelihood techniques. The 99.9 percent lower bound curves for this data were estimated in accordance to standard statistical methods.

Table 2–8. LCF Testing of PWA 1490 in 1000 psig Hydrogen Double Notch LCF Specimen (FAT 15002), Frequency 30 cpm

Sample Number	*Environment**	*Temperature C° (°F)*	*Total Srain Range (%)*	*Max Stress (ksi)*	*Cycles to Failure*	*Crack Origin*
D3	GH_2	26.7 (80)	2.18	120	5,109	Notch Surface
D	GH_2	26.7 (80)	2.18	100	9,539	Notch Surface
D2	GH_2	26.7 (80)	2.18	80	21,941	Notch Surface
F	GH_2	26.7 (80)	2.18	60	60,475	Notch Surface
F1	GH_2	26.7 (80)	2.18	50	83,866	Notch Surface

*GH_2 - 1000 psig Hydrogen Environment Containing Less Than 1 ppm O_2

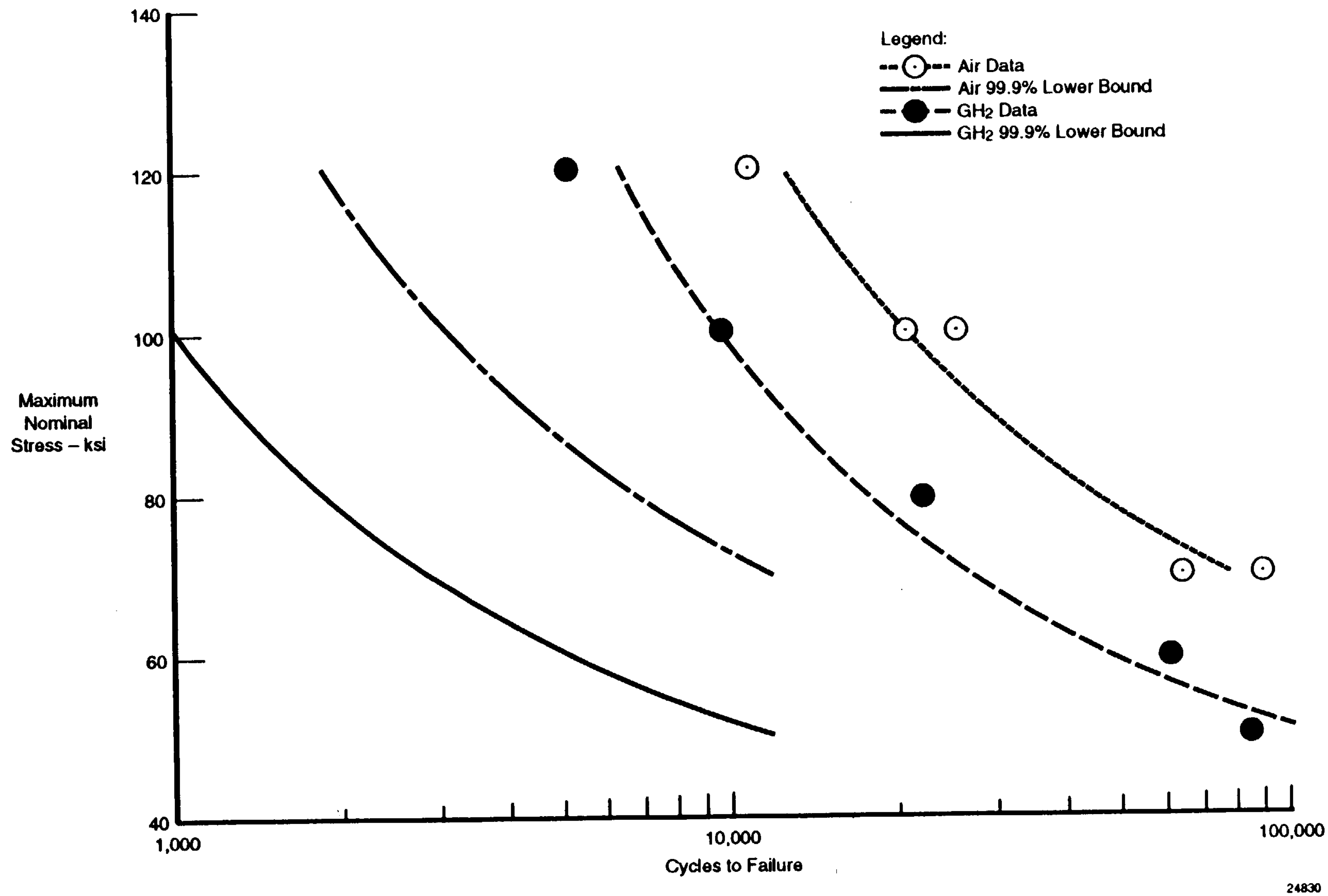


Figure 2–3. LCF Testing of PWA 1490 Double Notch Specimens Was Performed in Air and psig Hydrogen at 26.7°C (80°F). Cyclic Frequency = 10 cpm, $R\sigma$ = 0.05, K_t = 2.18 Conclusion: 2X Debit by 1000 psig Hydrogen at Room Temperature

2.5.2 DOUBLE NOTCH LCF AT 1000° F

Low-cycle fatigue testing of PWA 1490 at 537.8°C (1000°F) was performed in servo-hydraulic test machines, with load feedback control, using double notched (K_t = 2.18) LCF specimens. Baseline air testing was performed in a standard air environment at atmospheric pressure. Hydrogen testing was performed in a 1000 psig environment with less than 1 ppm oxygen. The tests were run at a stress ratio (R_σ) of 0.05 at a cyclic frequency of 10 to 30 cpm.

Results of the LCF tests are presented in Table 2–9 and in Figure 2–4. Mean curves, for the air and hydrogen data, were established using maximum likelihood technique. Lower bound curves for this data (99.9 percent) were estimated in accordance to standard statistically methods.

Table 2–9. LCF Fatigue Testing of PWA 1490 (Microcast INCO 718) Double Notch LCF Specimens (FAT 15002), $R\sigma$ = 0.05, Frequency – 10 to 30 CPM

Sample Number	Environment*	Temperature C° (°F)	Stress Concentration	Max Stress (ksi)	Cycles to 1/32 In. Crack	Cycles to Failure
4	GH_2	537.8 (1000)	2.18	140.0	—	2,602
3	GH_2	537.8 (1000)	2.18	100.0	—	9,212
2	GH_2	537.8 (1000)	2.18	100.0	—	10,336
1	GH_2	537.8 (1000)	2.18	80.0	—	20,973
5	GH_2	537.8 (1000)	2.18	60.0	—	+144,760 **
5	Air	537.8 (1000)	2.18	140.0	750	1,864
1	Air	537.8 (1000)	2.18	100.0	4,000	8,007
2	Air	537.8 (1000)	2.18	100.0	4,000	9,101
3	Air	537.8 (1000)	2.18	80.0	25,000	30,584
4	Air	537.8 (1000)	2.18	80.0	9,000	22,236
6	Air	537.8 (1000)	2.18	60.0	—	79,487

*Air- Standard Air Environment, Atmospheric Pressure
GH_2 - 1000 psig Hydrogen Environment Containing Less Than 1 ppm O_2
**Test Terminated Prior to Specimen Failure, Treated as a Censored Data Point

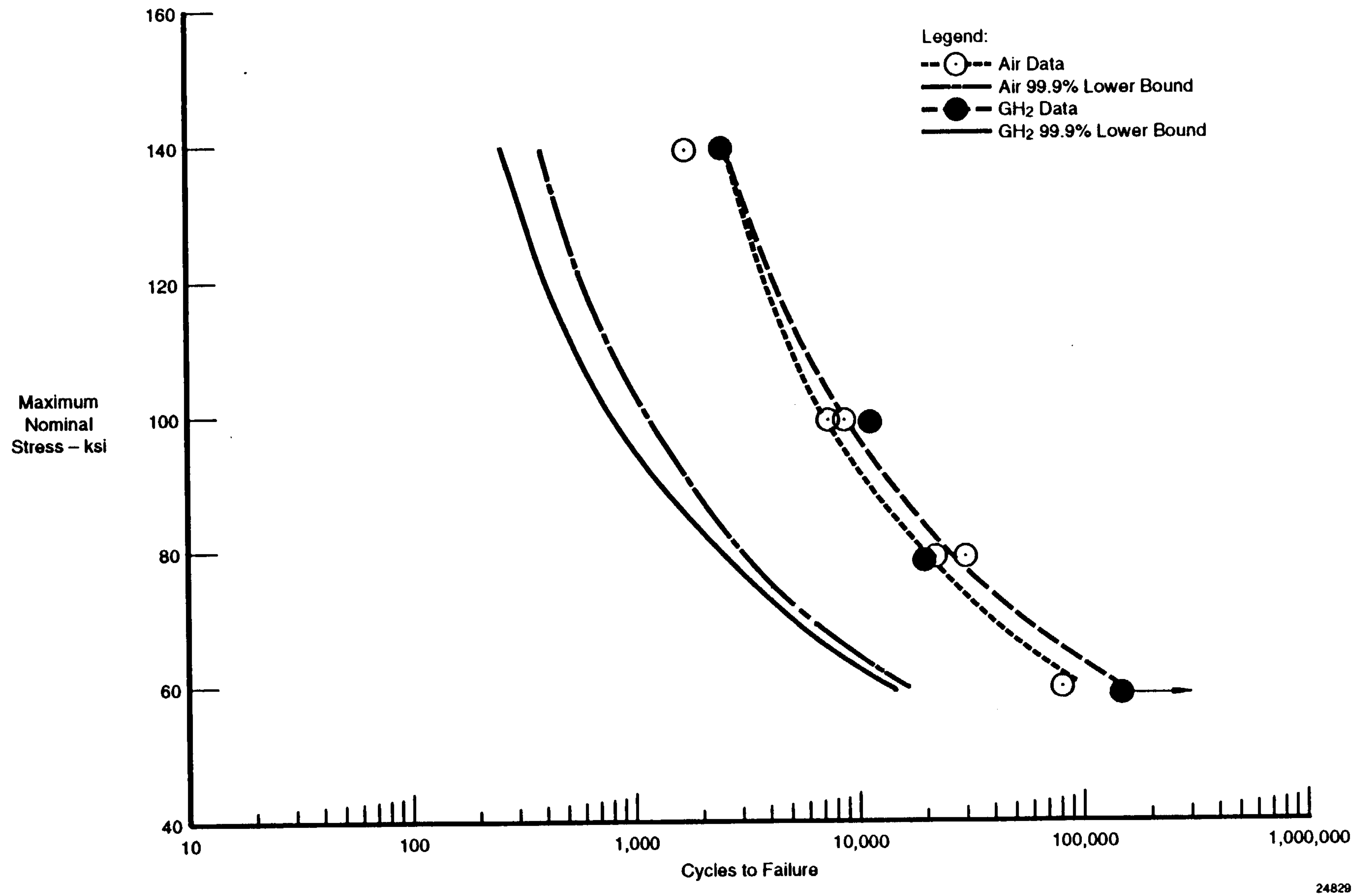


Figure 2–4. *LCF Testing of PWA 1490 : Load Control Fatigue Testing of Double Notched LCF Specimens (FAT 15002) Was Performed in Standard Air Environment and in 1000 psig GH_2 at 537.8°C (1000°F) – Cyclic Frequency = 10 to 30 cpm, $R\sigma$ = 0.05, K_t = 2.18*
Conclusion: No Significant Debit by 1000 psig Hydrogen at 537.8°C (1000°F)

2.6 SMOOTH HIGH-CYCLE FATIGUE

Smooth high-cycle fatigue (HCF) specimens (K_t = 1) were machined from SSME-ATD fuel inlet housing S/N 063.0. Specimens were tested in 1000 psig hydrogen at room temperature and 537.8°C (1000° F). The test were run axially at a stress ratio ($R\sigma$) of -1.0 (fully reversed stress cycle) and a cyclic frequency of 30 Hz to failure or runout at 10^7 cycles. Results of the requested HCF tests are presented in Table 2–10, and in Figure 2–5.

Mean curves were established using maximum likelihood techniques. Lower bound curves (-99.9 percent) for this data were estimated in accordance to standard statistical methods. Both the mean and lower bound curves were extrapolated out to 10^8 cycles.

Figures 2–6 and 2–7 compare the resulting data from HCF tests in hydrogen to baseline air data. The 1000 psi hydrogen caused no significant debit in HCF life at 537.8°C (1000°F) or at room temperature.

Table 2–10. HCF Testing of PWA 1490 HCF Specimen (FML 100721), $R\sigma$ = -1.0, FR EQ = Hz

Sample Number	*Environment**	*Temperature C° (° F)*	*Stress Concentration*	*Alt Stress (ksi Peak)*	*Cycles to Failure*	*Comments*
C06	GH_2	26.7 (80)	1.00	78.6	162,615	
C08	GH_2	26.7 (80)	1.00	78.6	102,200	Uploaded from 39 ksi
C07	GH_2	26.7 (80)	1.00	58.6	286,000	
B17	GH_2	26.7 (80)	1.00	58.6	202,125	
B16	GH_2	26.7 (80)	1.00	48.6	10,000,000	Did not fail **
C08	GH_2	26.7 (80)	1.00	38.6	10,000,000	Did not fail ***
B15	GH_2	537.8 (1000)	1.00	70.0	59,035	Uploaded from 40 ksi
C12	GH_2	537.8 (1000)	1.00	60.0	153,095	Uploaded from 30 ksi
C09	GH_2	537.8 (1000)	1.00	60.0	105,979	
C13	GH_2	537.8 (1000)	1.00	50.0	735,500	Uploaded from 40 ksi
B14	GH_2	537.8 (1000)	1.00	50.0	162,875	
B15	GH_2	537.8 (1000)	1.00	40.0	15,550,000	Did not fail ****
C13	GH_2	537.8 (1000)	1.00	40.0	11,160,000	Did not fail ****
C12	GH_2	537.8 (1000)	1.00	30.0	14,730,000	Did not fail ****

*GH_2 - 1000 psig Hydrogen Environment Containing Less Than 1 ppm O_2
**Treated as a Failure Point in the Regression
***Not Included in the Regression
****Treated as a Censored Data Point in the Regression

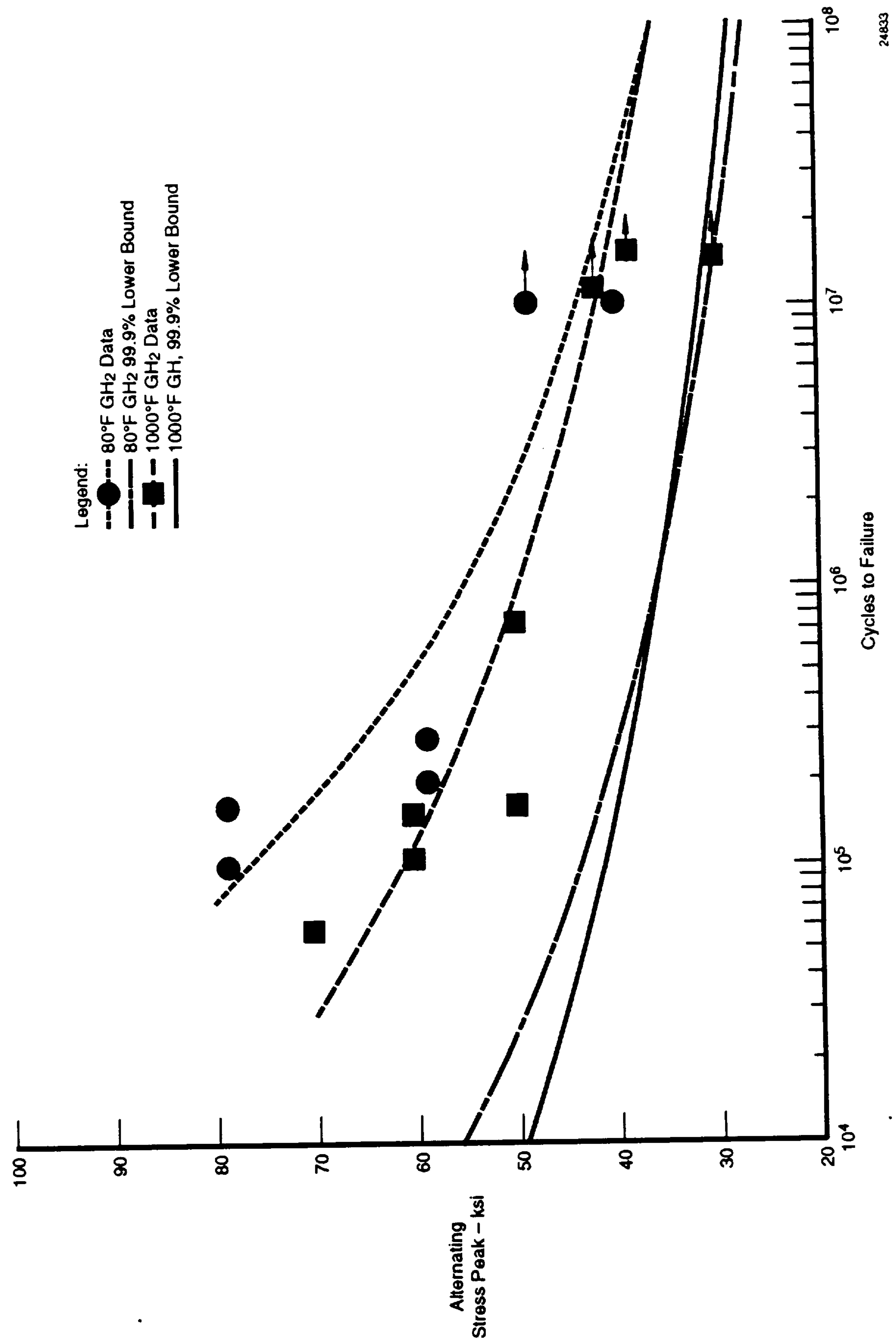


Figure 2–5. *High-Cycle Fatigue Testing of PWA 1490 Specimens Was Performed in 1000 psig GH_2 at 26.7°C (80°F) and 537.8°C (1000° F), Cyclic Frequency = 30 Hz, R_σ = -1.0, K_t = 1.00*

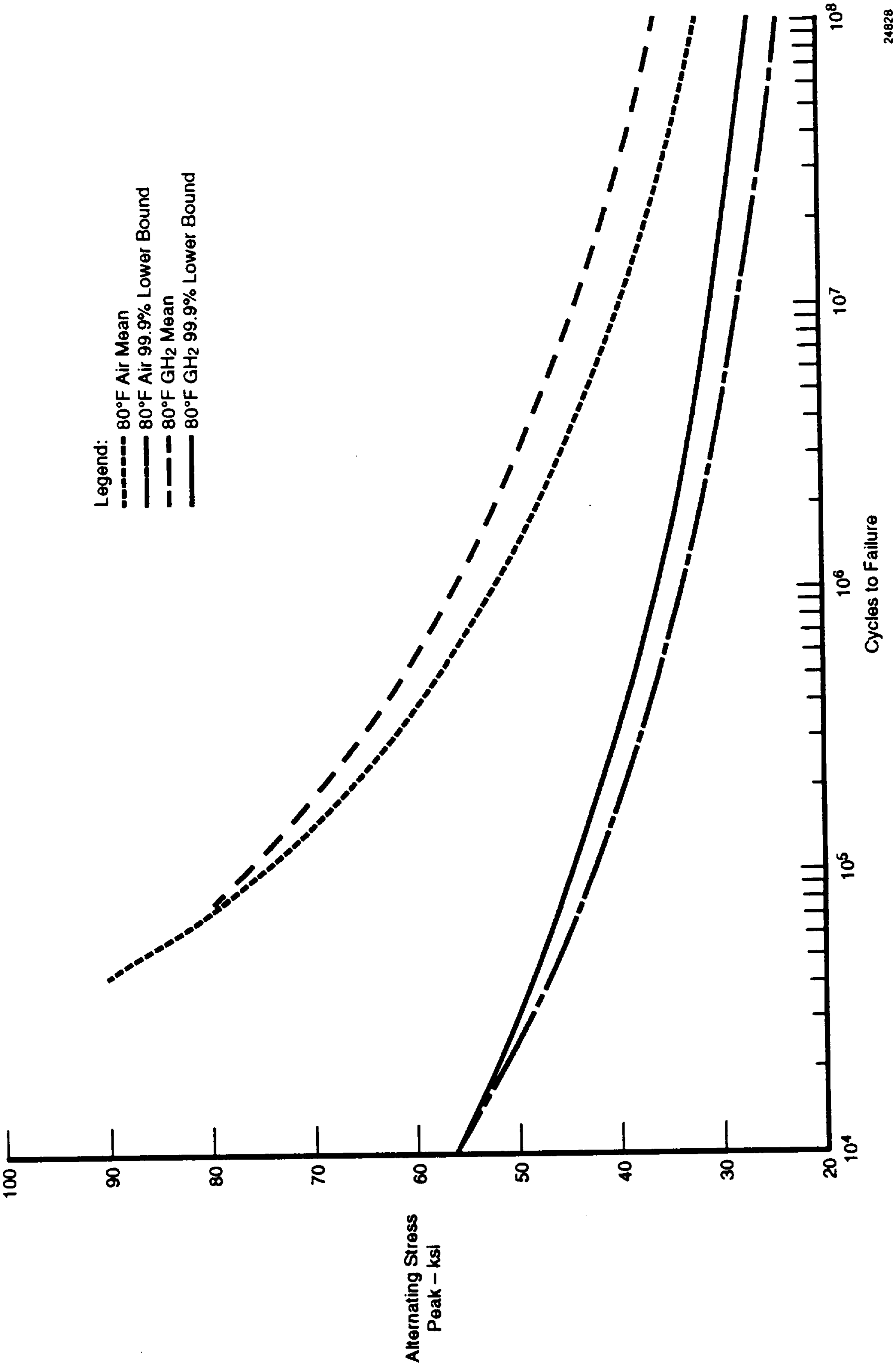


Figure 2–6. PWA 1490 HCF Comparison of Hydrogen verses Air at 26.7°C (80°F): Comparison Between 1000 psig Hydrogen and Atmospheric Pressure Air 26.7°C (80°F) Mean and Lower Bound HCF Curves, Cyclic Frequency = 30 Hz, R_σ = -1.0, K_t = 1.00 Conclusion: No Significant Debit by 1000 psig Hydrogen at Room Temperature

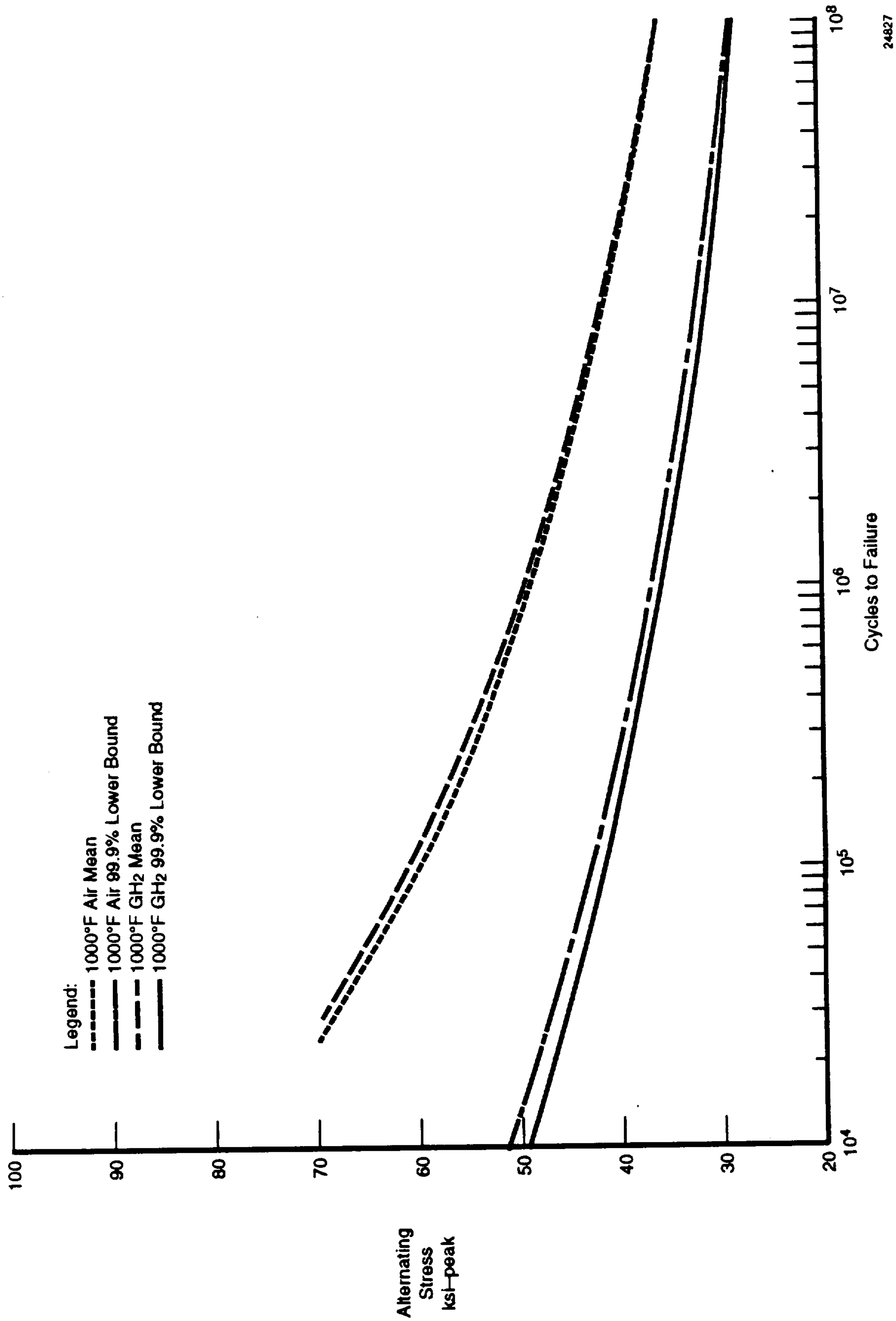


Figure 2-7. *PWA 1490 HCF Comparison of Hydrogen verses Air at 537.8°C (1000°F): Comparison Between 1000 psig Hydrogen and Atmospheric Pressure Air 537.8°C (1000°F) Mean and Lower Bound HCF Curves, Cyclic Frequency = 30 Hz, R_σ = -1.0, K_t = 1.00*

Conclusion: No Significant Debit by 1000 psig Hydrogen at Room Temperature

2.7 CRACK PROPAGATION

Two crack growth (da/dn) tests were performed on PWA 1490 material in 1000 psi Hydrogen at room temperature. The analysis and reduction of the crack growth test data was not complete at the time this report was published. This data will be made available at a later date.

2.8 FRACTURE TOUGHNESS

One compact specimen fracture toughness test was performed on PWA 1490 material from a SSME-ATD fuel pump inlet housing. This specimen was tested in 1000 psi Hydrogen at room temperature. Plane strain conditions were not met due to the thickness of the specimen. The high toughness of PWA 1490 requires a thickness greater than the standard compact fracture toughness specimen. In place of stress intensity factor (K_{IC}) a strength ratio of 1.295 was calculated. The strength ratio is the total stress (P/A = MC/I) at maximum load divided by the yield strength.

SECTION 3.0
SUMMARY

Fine grain Inconel 718 (PWA 1490), exhibited outstanding mechanical properties at room temperature and 537.8°C (1000°F) in hydrogen up to a pressure of 1000 psig. PWA 1490 had no significant degradation in tensile, high-cycle fatigue, or fracture toughness properties when exposed to 1000 psig hydrogen. Smooth and notch low-cycle fatigue at 537.8°C (1000°F) and 1000 psi hydrogen exhibited no hydrogen embrittlement degradation, but did show a debit at room temperature and 1000 psig hydrogen. However, this debit does not preclude the use of PWA 1490. The debited PWA 1490 has a 1000 cycle life at the 99.9 percent lower bound for a 0.7 percent strain range or 100 ksi stress. This level of LCF capability would be sufficient for a turbine housing application at the relatively low-pressure of 1000 psig.

2.7 CORNER SEAL EVALUATION

In an effort to improve liquid oxygen turbopump reliability an investigation of the optimum corner seal to improve thrust piston capability was undertaken. As part of this task a pressurized water flow rig was created and instrumented to test various STME thrust balance corner seal configurations. The test results were used to anchor an analytical corner seal and pressure drop model. The focus of this task was expanded to include optimizing the design of corner seals and characterizing their performance for use in the analytical corner seal prediction model.

The optimization method chosen was the Taguchi test method and evaluation of results. The large number of design parameters used in corner seals necessitated the use of two Taguchi test matrices. The first was a scope reduction to determine which parameters had the most effect on corner seal restrictiveness. The second Taguchi test matrix optimized the resulting parameters of the scope reduction tests. Finally the optimized sample was characterized and the analytical model anchored.

Results of the optimized sample gave a seal design almost twice as restrictive as the analytical predictions prior to this test program. An unexpected benefit of this test program was increasing seal restrictiveness with increasing axial overlap. This was not believed to occur prior to this test program.

This section contains objectives, work description and accomplishments along with the final report of the corner seal water rig test.

SPACE TRANSPORTATION PROPULSION TEAM

OXYGEN TURBOPUMP

Corner Seal Evaluation

- **Objective**
  - Determine an optimum corner seal configuration to enhance the thrust piston capability of the oxygen turbopump
- **Work Description**
  - Involves procurement and fabrication of plexiglass water flowrig with interchangeable configurations. Instrumentation includes static pressures and flow measurements of water flow data. Record pressure drop vs. seal clearance and determine optimum seal geometry, and provide documentation of test.
- **Significant Accomplishments**
  - Fabricated waterflow rig.
  - Optimized corner seal configuration for use in thrust balance / flow analysis.
  - Final report issued.

prepared for

NLS/STME Advanced Development Program

Corner seal water rig - final report

December 1992

Mark S. Schroder
Jorge A. Kuryla

United Technologies Corporation - Pratt and Whitney Aircraft Company
Government Engines and Space Propulsion Division
West Palm Beach Florida

Table of Contents

Table of Figures

Abstract:

A pressurized water flow rig was designed and built to test scaled test samples of the STME thrust balance corner seals. The purpose of the corner seal test program shifted from its original intent. It was planned to test various features of the seal at several radial and axial positions, that were believed to improve its restrictiveness. These results were used to anchor an analytical corner seal flow and pressure drop model. The focus was expanded to include optimizing the design of corner seals and characterizing their performance for use in the analytical corner seal prediction model.

The optimization method chosen was the Taguchi test method and evaluation of results. The large number of design parameters used in corner seals necessitated two Taguchi test matrices. The first was a scope reduction to determine which parameters had the most effect on corner seal restrictiveness. The second Taguchi test matrix optimized the resulting parameters of the scope reduction tests. Finally the optimized sample was characterized and the analytical model anchored. The optimized sample was not characterized as extensively as had been hoped due to the suspension of the NLS/STME program.

Results of the optimized sample gave a seal design almost twice as restrictive as the analytical predictions prior to this test program. An additional benefit was realized for the optimized sample. It displayed an increasing seal restrictiveness with increasing axial overlap. This effect was not believed to occur prior to this test program

I. Description of Corner seals in rocket turbomachinery

During the explosion to full power and cut-off at shutdown, rocket turbomachinery experience extremely large variations in fluid pressure in the cavities enclosing the rotating components. In order to keep the shaft movement, due to these pressure variations, within the limits of the turbopump design, a shaft axial load balancing system is added to the turbopump design. The easiest and most efficient system developed, uses a shrouded pump impeller's front and back face as the mechanism to control shaft movement. This "thrust balance system" is designed to accommodate any unforeseen imbalances during off-design, transient start-up or shut-down operation, .

The key component that makes the "thrust balance system" function is a set of corner seals, located at the outer and inner diameter of the pump impeller's back-face (see Figure I-1). These seals change their restrictiveness and flow area as the shaft moves. By changing their flow restriction, the seals allow lower or higher pressure to develop in the on the pump impeller's back face. This results in a restoring force that counter act the shaft travel. A corner seal design has several goals to achieve. These goals are to maximize load capability of the thrust balance system by maximizing corner seal "restrictiveness" during tight gap operation (see Figure I-1), and minimizing corner seal "restrictiveness" during open gap operation. Another goal is to minimize thrust balance system flow since it is leakage from pump discharge and detrimental to pump efficiency and suction performance. A final goal of any corner seal design is to have its operation characterized so the thrust balance system can be confidently analyzed during all phases of operation. (see Fig. I-2 for summary)

II. Corner seals in the NLS/STME liquid oxygen turbopump

Balancing design, off-design, and transient loads during STME LOX turbopump operation requires a double corner seal at the outer and inner diameters of the shrouded pump impeller. The large size of the impeller necessitates large radial clearances on the OD corner seal, resulting in large amounts of flow leaking from the mainstream pump flow and a complex system in the impeller and housing to route the flow back to impeller inlet (see Fig. II-1). This type of "thrust balance system" with large leakage flow affects pump performance, housing structural reliability, cost, and manufacturing ease of the turbopump. Enhancements to the "thrust balance system" operation could be made if the corner seal were used to dramatically reduce the leakage flow while maintaining "thrust balance system" capability. When this project was conceived there was not a large volume of empirical information about the operation and behavior of corner seals. Also at this time, no calibrated analytical model existed for "thrust balance system" corner seals. Therefore, a test program was proposed for the STME LOX turbopump corner seals that would develop an understanding of their operation and provide data to calibrate the analytical corner seal model.

III. Corner seal rig test program proposal

A new type of corner seal design incorporating grooves was investigated in early 1991 using extrapolated CFD predictions of an enhanced labyrinth seal from a Texas A&M study. In that study, the geometry and flow field employed to model the labyrinth seal, closely matches those of a corner seal. Since the enhanced labyrinth seal showed substantial enhancement of performance, it was decided to apply these results to the STME LOX pump corner seals with the hope of increasing thrust balance system capability and reducing overall leakage.

To evaluate the improvements an enhanced corner seal (see Fig. III-1) might deliver to the thrust balance system, the uncalibrated corner seal leakage model of the STME LOX pump flow balance model was modified by increasing the "restrictiveness" of the standard corner seal by 70%. This level was derived from the CFD predictions for the enhanced labyrinth seal. The updated model showed an increase in positive (toward the turbine) loading due to reduced pressure along the impeller's back-face and lower flowrate. To return to the design thrust load, the ID corner seal (ref. Fig. II-1) clearance was reduced, thereby increasing the pressure along the impeller's back-face with even lower leakage flow. See Figures III-2 & -3 for leakage predictions and resulting increase in thrust balance capability.

The enhanced corner seal study showed the following advantages for the STME LOX turbopump design: 1.) increased thrust piston capability, 2.) decreased thrust balance system flow, 3.) increased pump efficiency (lower H.P. requirement), 4.) improved suction performance, 5) decreased complexity and cost of housing design, by eliminating recirculation tubes, as well as 6.) increased structural integrity of the impeller resulting from reduced number of recirculation holes through base.

These promising results for the turbopump design were ample encouragement to examine what would be required to create and calibrate an analytical tool for corner seal predictions which could then be used in the 1D flow network of secondary flows as well as the main pump design flow balance model.

The original proposed test matrix to develop an analytical tool was:

Grooved corner seal design (similar to enhanced labyrinth seal):
3 groove design (different - L/D)
3 axial positions - centered, +0.015", -0.015"
3 flowrates
2 clearance levels
54 total tests 6 configurations

Ungrooved corner seal design (similar to standard seal):
1 ungrooved design
3 axial positions - centered, +0.015", -0.015"
3 flowrates
2 clearance levels
18 total tests 2 configurations

The most cost effective method of achieving the proposed Test Matrix was a simplified non-rotating water flow rig tested at Pratt & Whitmey's Aerothermal Design Lab. Section IV describes the resulting water flow rig, its features, and the Design Lab's capabilities.

IV. Corner seal rig and facility features

To begin water flow testing a rig had to be designed to hold the grooved and ungrooved test samples. It would need to have flow visualization capabilities as well as easy access to the test samples. Part of the proposed test matrix was to vary the "rotor's" axial position, requiring it to be moved relative to the static piece. The feasibility of incorporating the tangential velocity component, found in the actual corner seal, was investigated. Unfortunately, the angle at which the test sample would have to be set in order to simulate the tangential velocity of flow in the seal required a test section that exceeded the water table's dimensions (ref. Fig IV-4). The compromise was thus made to examine the through flow component only. This was believed to be a valid approximation since the flow must travel axially through the seal regardless of velocity vector. The through flow component was also consistent with the current analytical modelling technique. The shape and operation of the corner seal is believed to be a function of total through flow and therefore the overall seal "restrictiveness" should not be strongly affected by velocity vector. This effect remains to be quantified through seal characterization in the pump water flow rig.

The resulting corner seal rig is a 8" X 8" X 30" channel (see Figure IV-2). This allowed a large enough test sample to be installed such that pressures measured at the center of the sample would not be subject to end-wall effects. The size of the channel resulted in slow, uniform flow supplied to the test sample. The inlet chamber is approximately 6.5 " long. Included in this chamber is an inlet pipe diffuser to eliminate the inlet flow impinging on the back wall. The flow from this chamber then passes through a flow straightener and a screen onto the supply channel. The static pressure drop associated with this configuration, measured from the inlet, to a location upstream of the test sample, was 0.2 - 0.4 psia.

Figure IV-1 displays some of the features of the test rig. Instrumentation for the test sample and rig are shown in Figure IV-3. Figure IV-5 shows a calibration curve for the flow meter on the test stand which gives an idea of the capability of the facility.

V. Taguchi optimization test program for an improved corner seal design

After examining the number of design parameters involved with corner seal geometry, the goal of the corner seal program shifted from evaluating a few cases with features believed to improve sealing performance (described in Section III), to that of optimizing the existing corner seal design. The large number of dimensions necessitated using Taguchi optimization techniques to produce an optimized design. The pressure drop and flow data from the Taguchi Test matrix would be used to calibrate an analytical corner seal model. Additionally, it would provide insight into the general operation of corner seals in an incompressible medium.

The large number of dimensions needed to define a corner seal required two sets of Taguchi test matrices. The first matrix would examine all dimensions in an effort to reduce the number of parameters that would be examined for optimization. The resulting test matrix was an L12 Taguchi test matrix, with 11 parameters of investigation in 12 tests as shown in Figure V-1. Note dimension F and V were fixed with each other. The axial position (K&L) was held constant for all tests, as well as the radial position (I&J). There was some variation in radial position from test to test due to Plexiglass tolerances on the scaled test samples (3.75 times turbopump dimensions).

VI. Taguchi scope reduction test results

The ranked response of the scope reduction test matrix is shown in Figure V-2. The response variable in the test matrix was delta pressure. It was measured by static wall taps upstream and downstream of each test sample. Data was taken at several flow rates, although the response ranking was examined only at 50 Gal/min. This represented the highest possible flow that existed on all test samples except for trial or test number 5. It is believed that this sample was inadvertently tested at a much smaller radial clearance, therefore the maximum attainable flowrate was only 28 gal/min. For this one case the flow data for response ranking was extrapolated from 28 to 50 gal. / min. The results of Figure V-2 show that parameters G and U have the largest influence on pressure drop across a corner seal.

Delta pressure was used as the response variable because it represented a direct measure of a corner seal's restrictiveness due only to seal geometry changes for a given flow and area. Figure I-1 describes how in order to obtain the greatest thrust balance capability, the largest delta pressure possible is desired across a tight gap corner seal.

The resulting test sample geometries and ranking by delta pressure are shown in Figures V-3 & 4. The overall seal K-loss is also shown for each sample. An independent statistical analysis of the scope reduction test results was performed by Pratt & Whitney's statistical analysis group confirming the rank of the scope reduction test results. The four primary influence parameters are B, G, U, V, listed in order of importance.

Results from the scope reduction tests were evaluated by two methods. The standard method of analyzing Taguchi tests, shown in Figure V-2, is to rank the parameters (corner seal dimensions, ie. B, C, etc.) in order of influence. The magnitude of influence is found by calculating, for each parameter, the average of its first level's response (delta P) and subtracting the average of its second level's response. The dimensions corresponding to the first (1) and second level (0) are shown above each parameter. The parameters with the largest difference between first and second level average response are those with the highest influence. The ranking of parameters highest to lowest is shown on the bottom line of Figure V-2. From this analysis method, we chose parameters G and U in order to optimize the corner seal design.

The second method used to evaluate the scope reduction results was to rank the test cases in order of response, as shown in Figures 3 & 4. Inspecting the test sample cross-sections it was found that samples with tall step heights (dimensions F & V) and narrow land widths (B & E), with K = L = 0 had the highest response (delta P). Therefore, B and E were fixed to the same dimension and would be used in the corner seal design optimization. The same was done for F & V.

VII. Taguchi Optimization test matrix

The results of the scope reduction Taguchi test matrix found four parameters B, G, U, and V as the primary dimensions that influenced the overall corner seal loss factor. The Taguchi optimization test matrix for these parameters and their interactions was created using the best tested level of each parameter (B,G,U,V) from the scope reduction tests, plus and minus 25% of that level. The resulting test matrix is shown in Figure VII-1.

Axial positions K & L would be varied together for each optimization test at the line-on-line and maximum open positions allowed by the turbopump bearings. This variation would quantify the K-loss of each configuration at the corner seal axial positions which determine the thrust balance system's capability. Refer to Figure I-2 for a reminder of the goals of corner seal design. Figure VII-2 shows a dimensioned cross section of the eight samples in the Taguchi optimization test matrix for the line-on-line axial position.

VIII. Taguchi Optimization matrix results

The overall goal for the optimization of a corner seal's design is to maximize the seal's restrictiveness in the tight gap or overlapped axial position and minimize its restrictiveness in the open axial position. For this reason the response variable used to evaluate the optimization test results was K-loss. Figure VIII-1 shows the ranked response of the Taguchi optimization matrix at the line-on-line position at 55 Gal/min. The top four are the GV interaction, dimension V, or step height, the GB interaction, and U, the inlet step dimension. In the axially open position ranking was predominantly based on exit geometry, where the top four parameters of influence are B seal pitch, GB interaction once again, GV interaction again, and G the exit expansion height. Dimension G has a weak influence compared to the first three. The ranking by pressure drop is shown for comparison at line-on-line, Figure VIII-3, and open axial position, Figure VIII-4. The ranking is slightly different than by K-loss, with G, U, GV, and V as the most influential factors for the line-on line case. The most influential factors for the axially open case were V, G, U, and GU.

Reviewing the previous paragraph one can visualize what factors are influencing the restrictiveness of a corner seal by observing the number of times a parameter is mentioned. The factors=time mentioned are, G=3, V=3, GV=3, U=3, GB=2, B=1, GU=1 and are listed in order of ranking.

Figure VIII-5 continues the data reduction of the optimization matrix by displaying the difference in K-loss for all samples at their respective axially open tested positions. The largest delta K regardless of tested axial position is the most desirable sample. Note that Sample 1 is a 2X scale of

Sample 8's dimensions (reference Fig. VII-2). Figure VIII-5 shows that Sample 4 has the largest delta K, even thought it was tested with the smallest axial gap.

Figure VIII-6 demonstrates the slope and trend of the different samples when tested at the axially open and line-on-line positions. Although Sample 4 has the highest slope, it does not have the highest K-loss level. Since Samples 8 and 1 are scaled to each other, and have similar K-loss and slope of K-loss, Sample 1 was chosen as the champion of the Taguchi optimization matrix.

IX. Optimized corner seal design and its characterization

The scope reduction test results, the optimization test results, the ranking of parameters of influence, as well as Figures VIII-5 & 6 were all used to determine the dimension of each parameter that would create the optimized corner seal geometry. The ranking of parameters from Section VIII recommended G at its highest level, V at its highest level, and finally U at its lowest level. Referring to Figure VII-2, sample 4 with a small value for U, yielded the largest delta K from line-on-line to axially open. Parameter B is recommended at its highest level because of the large response of sample 1. Figure IX-1 shows a cross section of the optimized corner seal geometry. The optimized sample is the same as sample 1 with the exception of the entrance height U set at the minimum level of 0.281" instead of sample 1's dimension of 0.469".

While sample 1 was being modified into the optimized geometry of Figure IX-1, news of the NLS program suspension was received. For this reason only limited characterization of the optimized sample could be completed. Figure IX-2 shows 5 test points of the optimized sample from open 0.028" (turbopump scale) to 0.029" overlapped, at the same clearance level used in the optimization matrix (0.11" in rig). The optimized sample has slightly higher (3-4%) K-losses at line-on-line and axially open than did sample 1 of the optimization matrix. For comparison, Figure IX-2 has the original pre-test analytical estimate of K-loss through the baseline corner seal (sample 1 scope reduction matrix, Figure VI-2), along with the optimized sample characterization.

X. Conclusions, Recommendations and comments

We regret being unable to fully characterize the optimized sample as originally planned. We had envisioned testing this sample at two additional radial clearances for a total of three, all at the same axial positions as shown in Figure IX-2. In addition, it had been planned to test the optimized sample in a tilted position to simulate impeller deflections that might occur in the turbopump's impeller. Impeller deflections could result in the corner seal having different flow areas through the first and second constrictions. This test would have been performed by applying a taper on the step from the first to the second constriction. Tilting the whole sample would produce results identical to a test at a more open axial position.

The main results of this program was the identification of the key design parameters that influence a corner seal' s restrictiveness. Although the final goal of fully characterizing an optimized corner seal geometry was not achieved, a great deal of information was learned through the Taguchi scope reduction and optimization test program. From this information a comprehensive analytical model was developed for use in future design and analysis of corner and variable restriction seals.

Thrust Balance System Operation

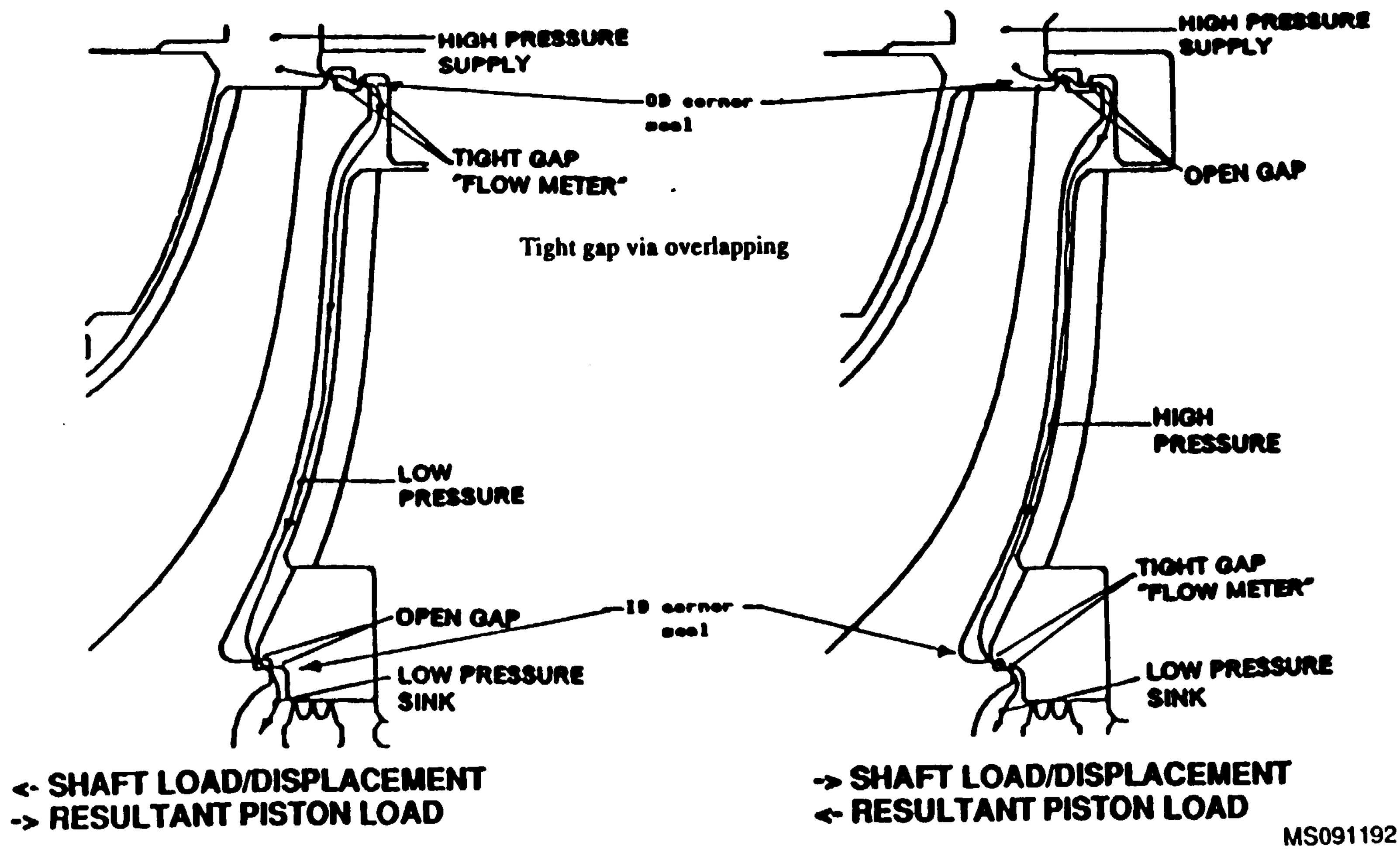


Figure I-1 Thrust Balance System Operation

Goals of Corner Seal Design

- Maximize load capability range of thrust balance system
- Minimize thrust balance system flow...since it is leakage from pump discharge
- Maximize corner seal "restrictiveness" during tight gap operation
- Minimize corner seal "restrictiveness" during open gap operation
- Characterize corner seal operation so thrust balance system can be confidently analyzed

Figure I-2 Summary of Corner Seal Functional Goals MS091192

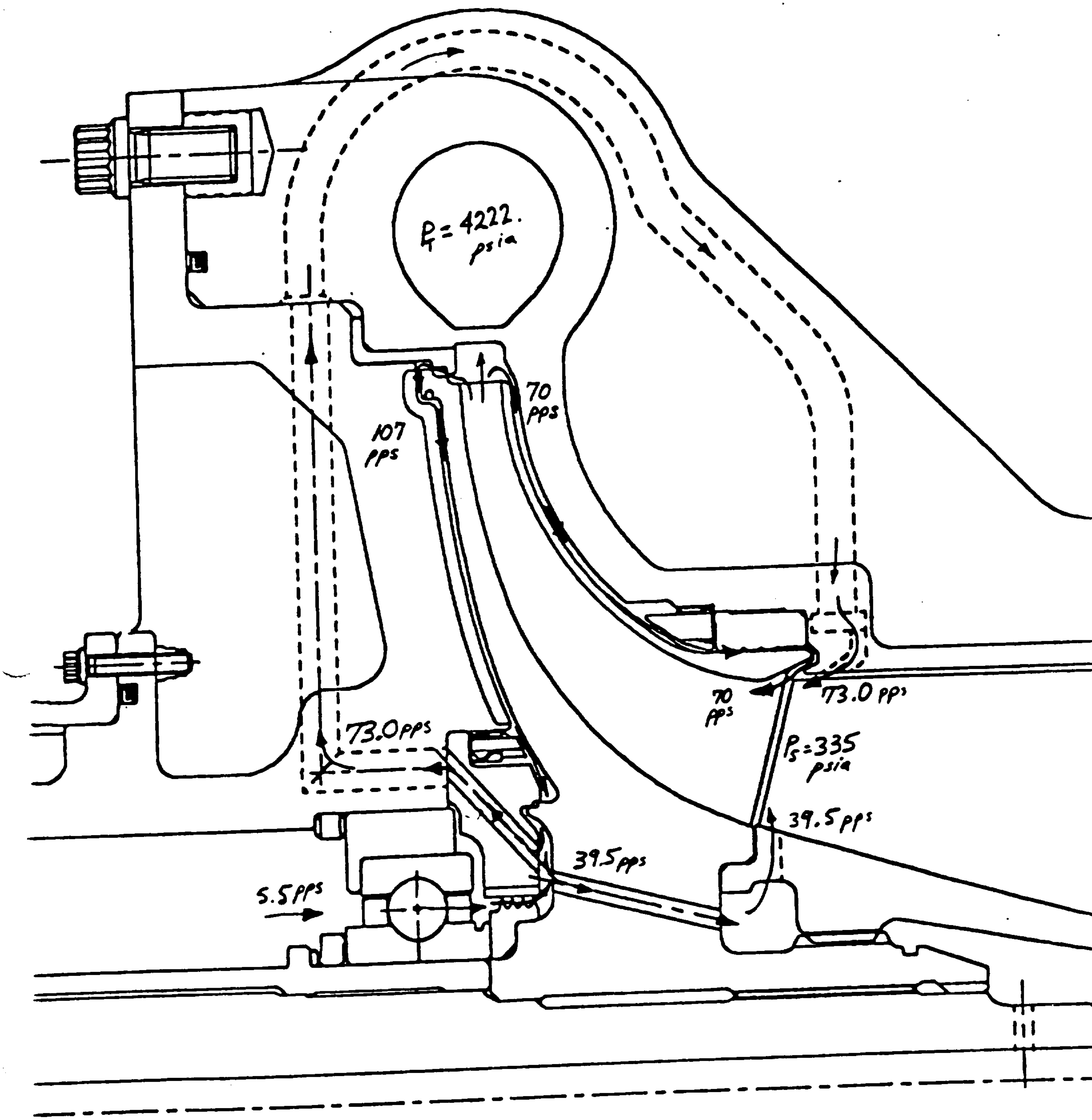
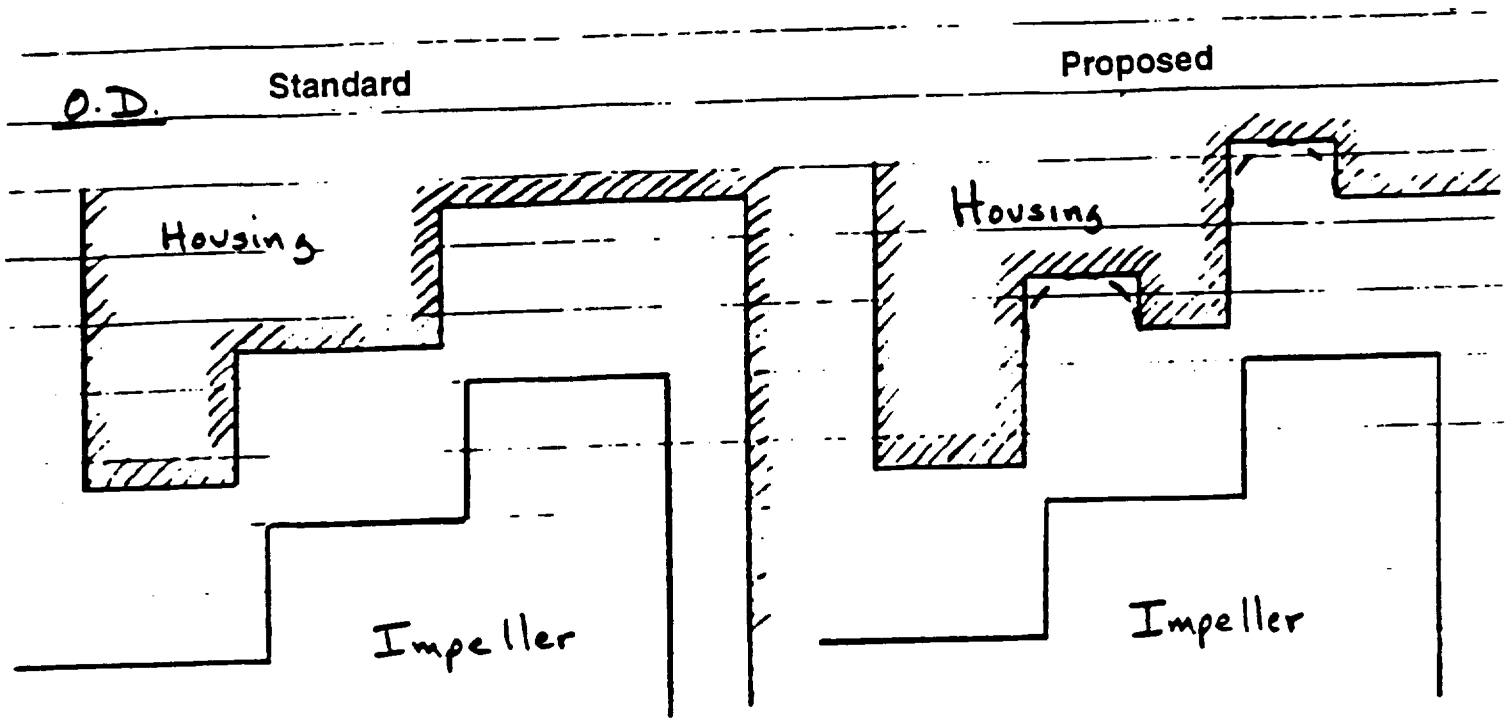


Figure II-1 STME LOX Pump Thrust Balance System Prior to Corner Seal Investigation

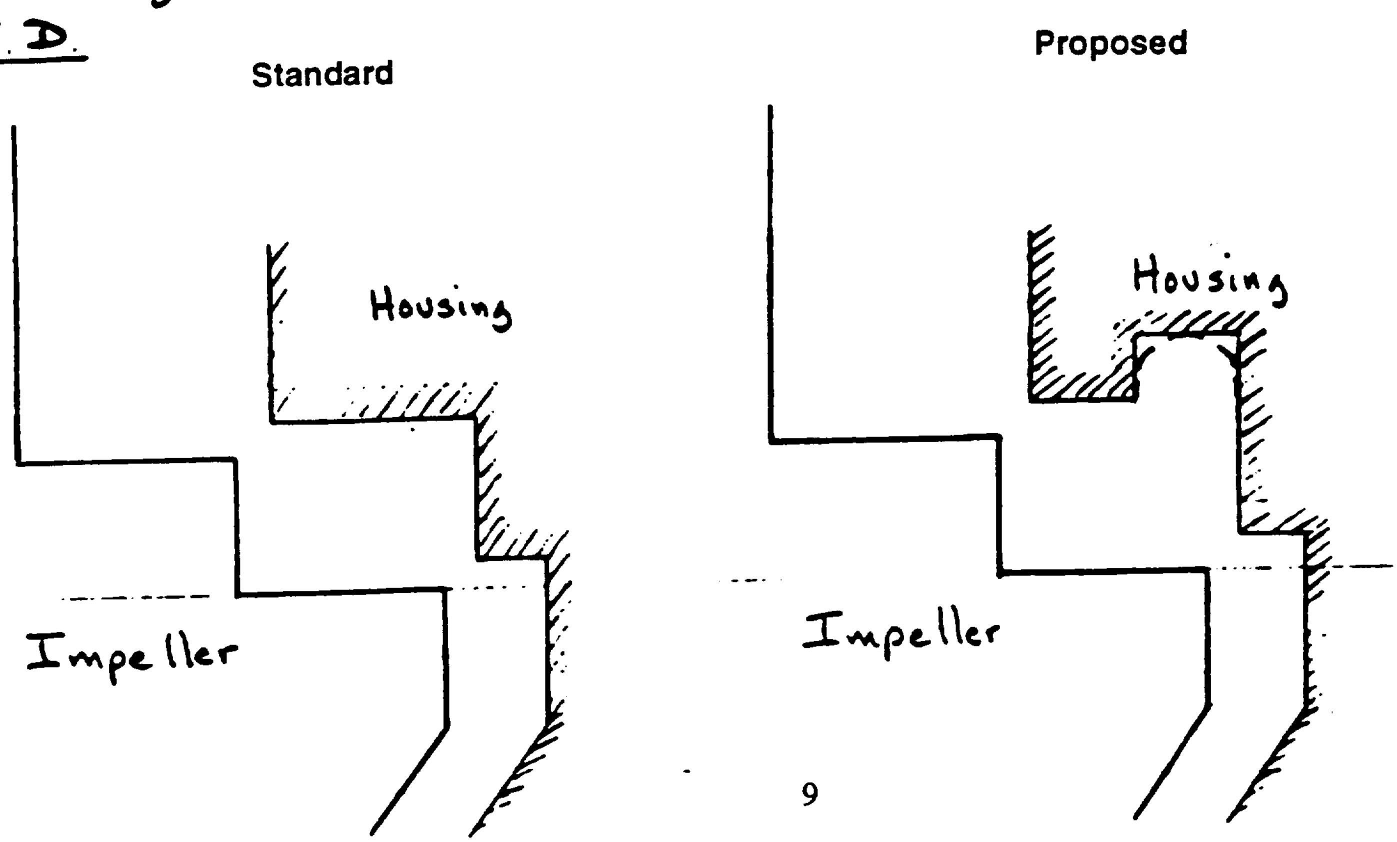
Figure III-1 Proposed Grooved Corner Seal Design

O.D.



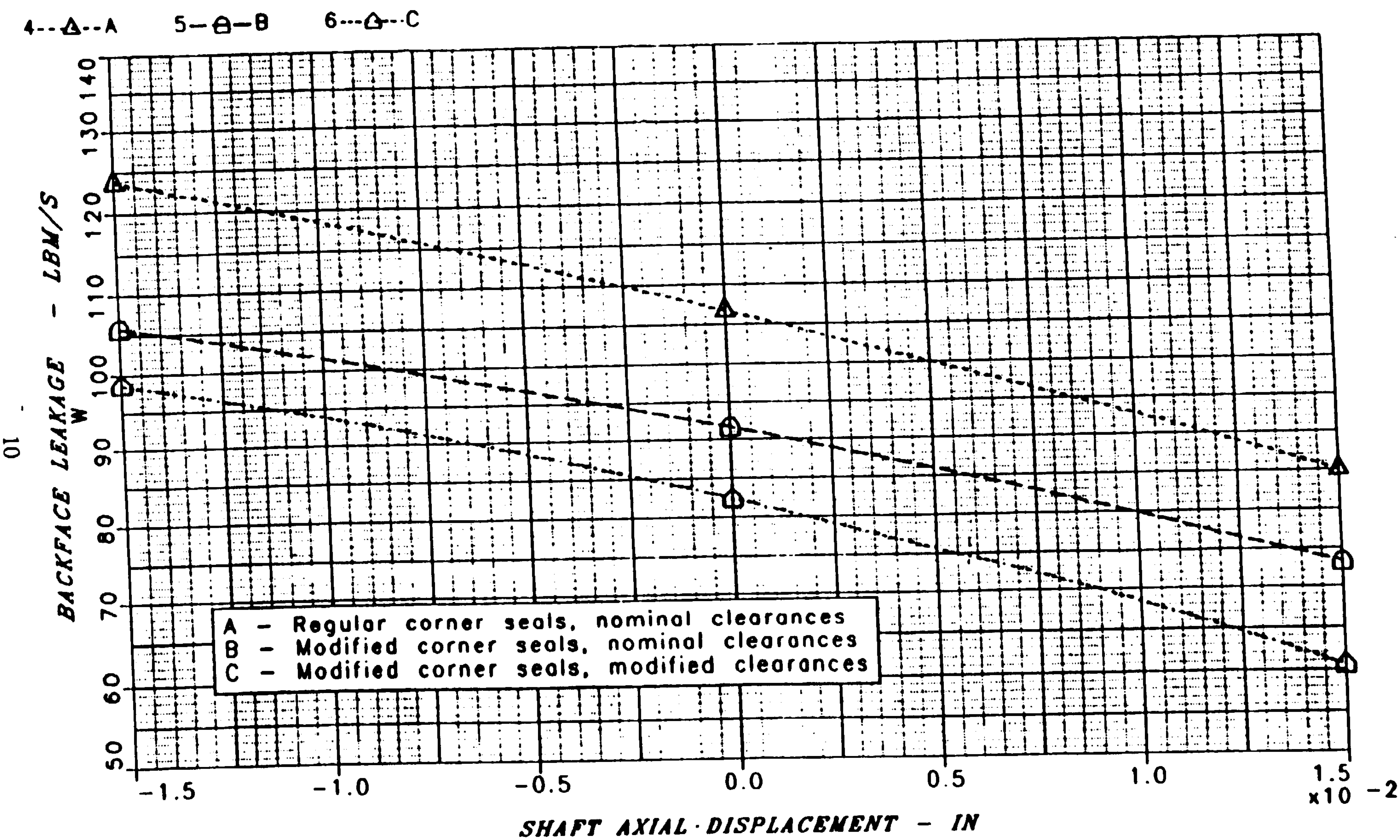
Addition of groove increases resistance coefficient by 70% - report by D.L. Rhode on SSME lab seals

I.D.



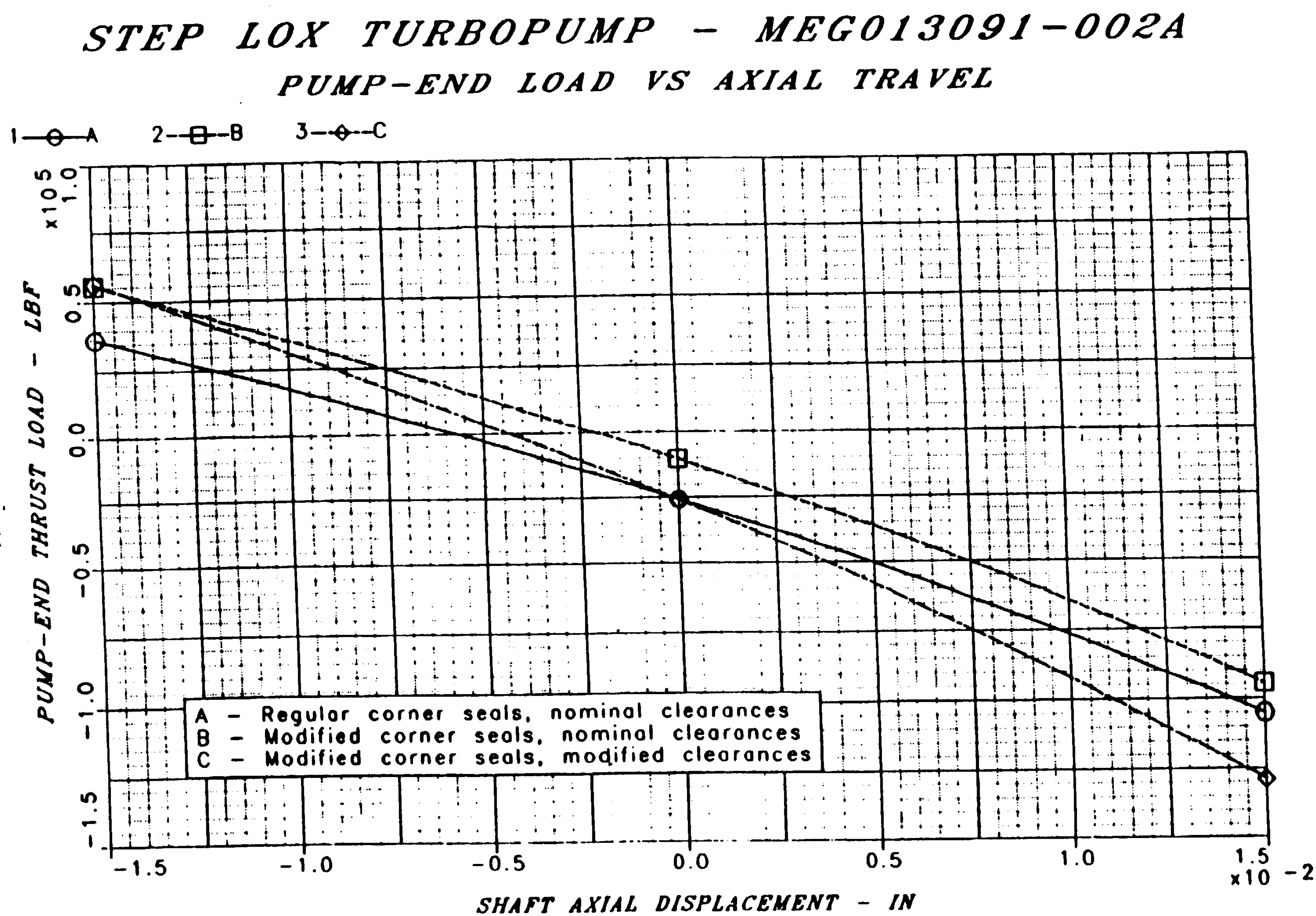
STEP LOX TURBOPUMP - MEG013091-002A

BACKFACE LEAKAGE VS AXIAL TRAVEL



03/20/91
L KURYLA

III-2 Enhanced Corner Seal Study - Flowrate



03/20/91
J. KURYLA

III-3 Enhanced Corner Seal Study - Thrust Piston Capability

Figure IV-1 STME Seal Rig Features

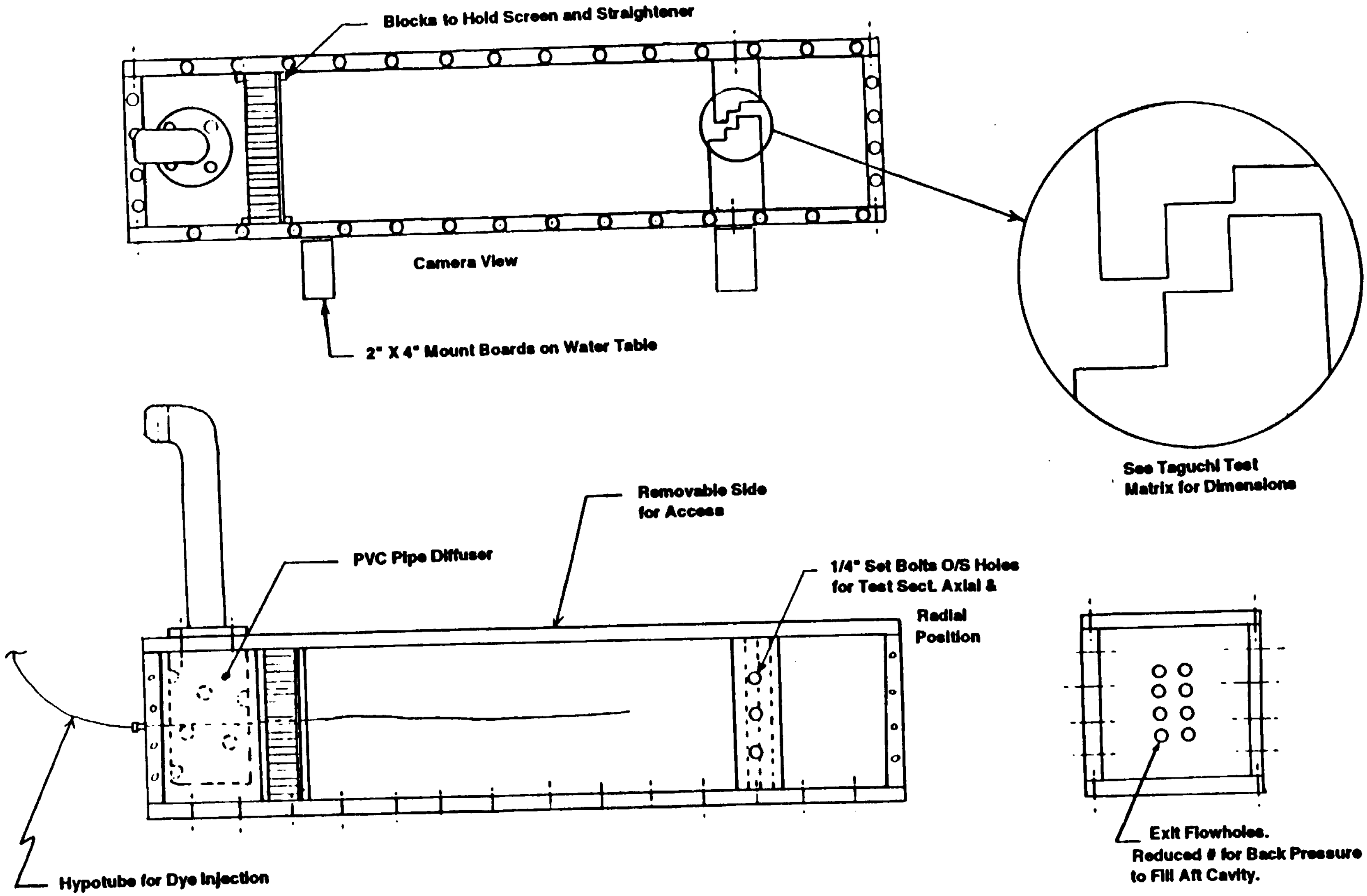


Figure IV-2   STME Corner Seal Rig Dimensions

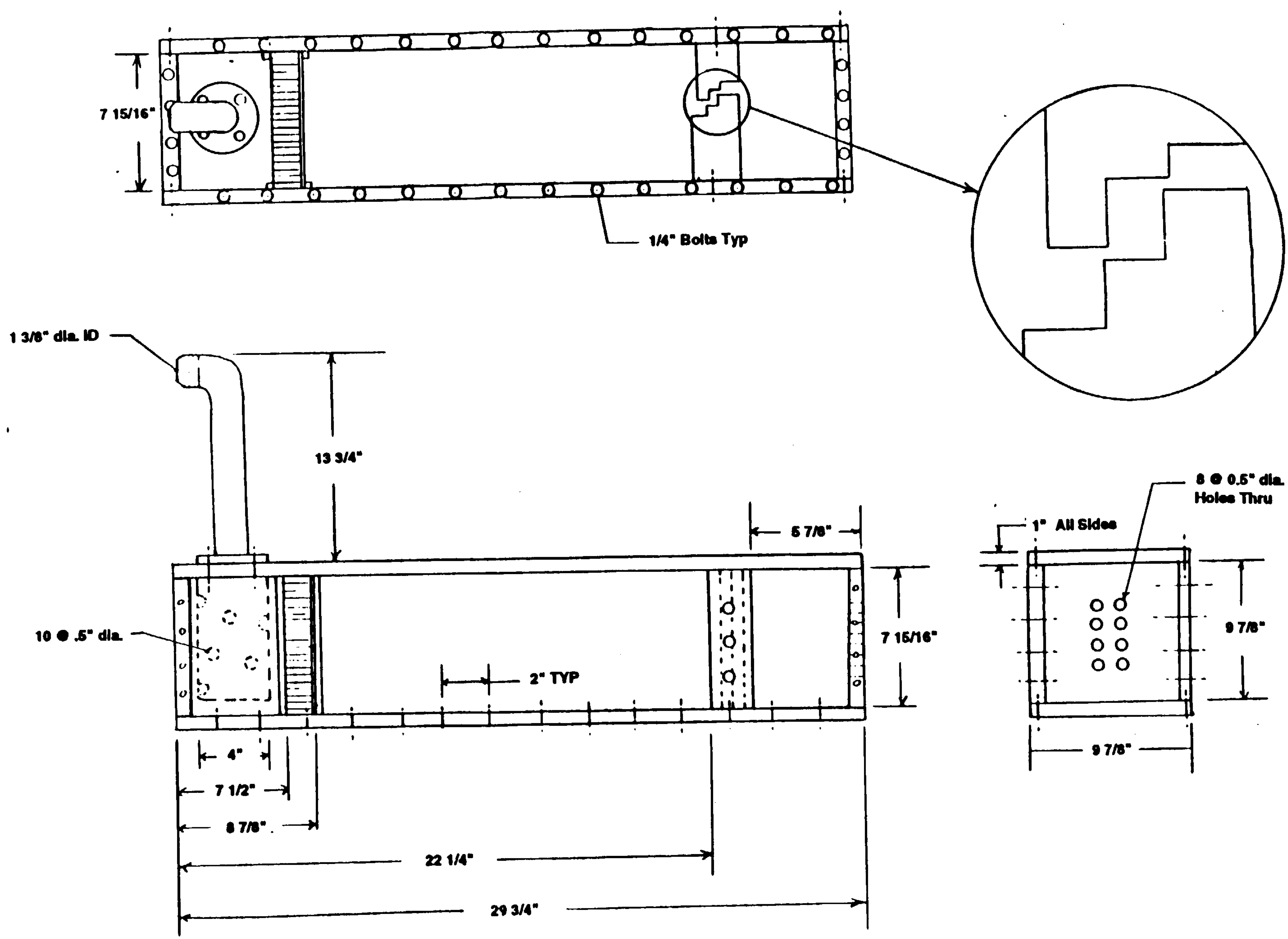
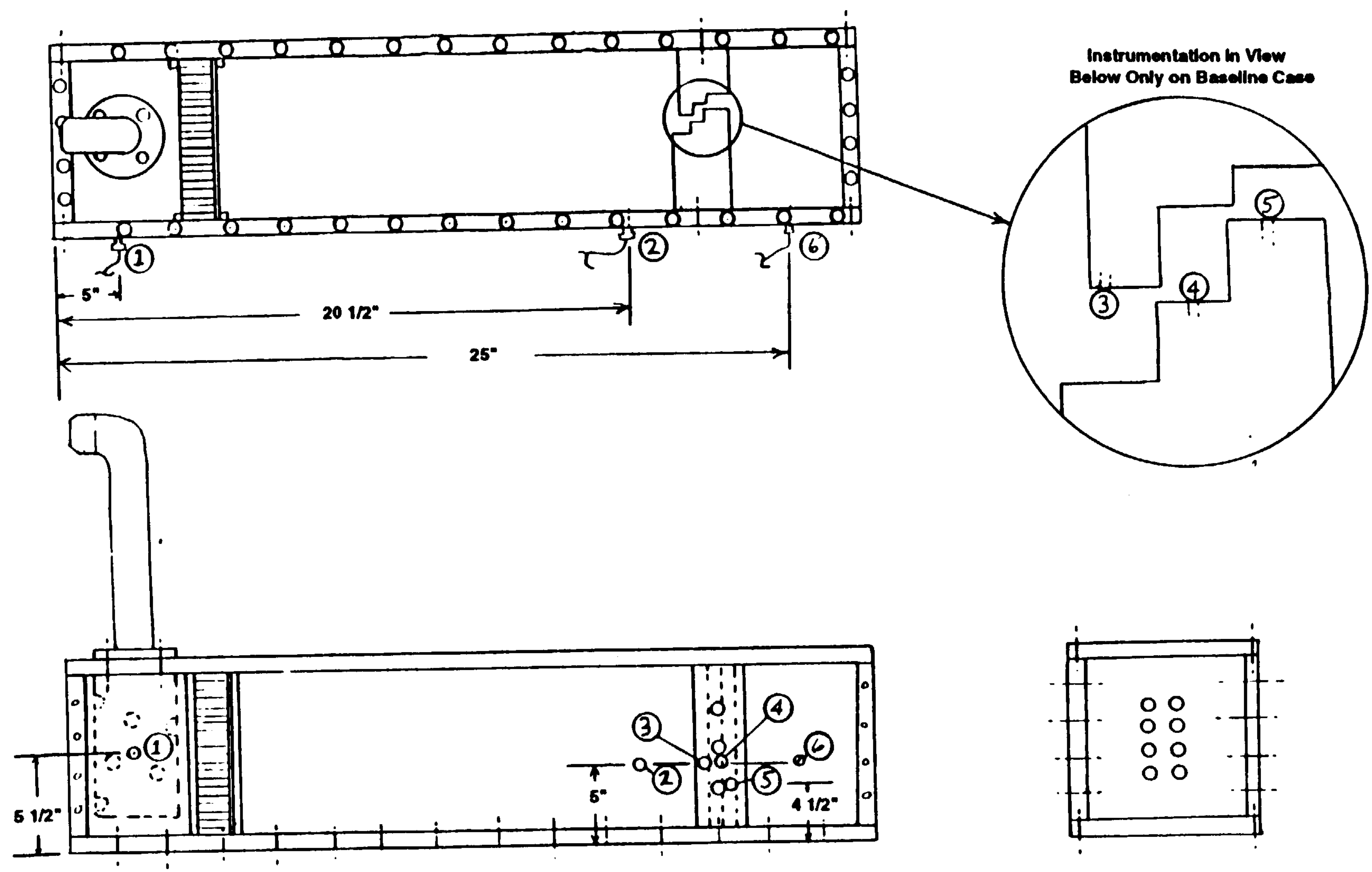


Figure IV-3 STME Corner Seal Rig Instrumentation



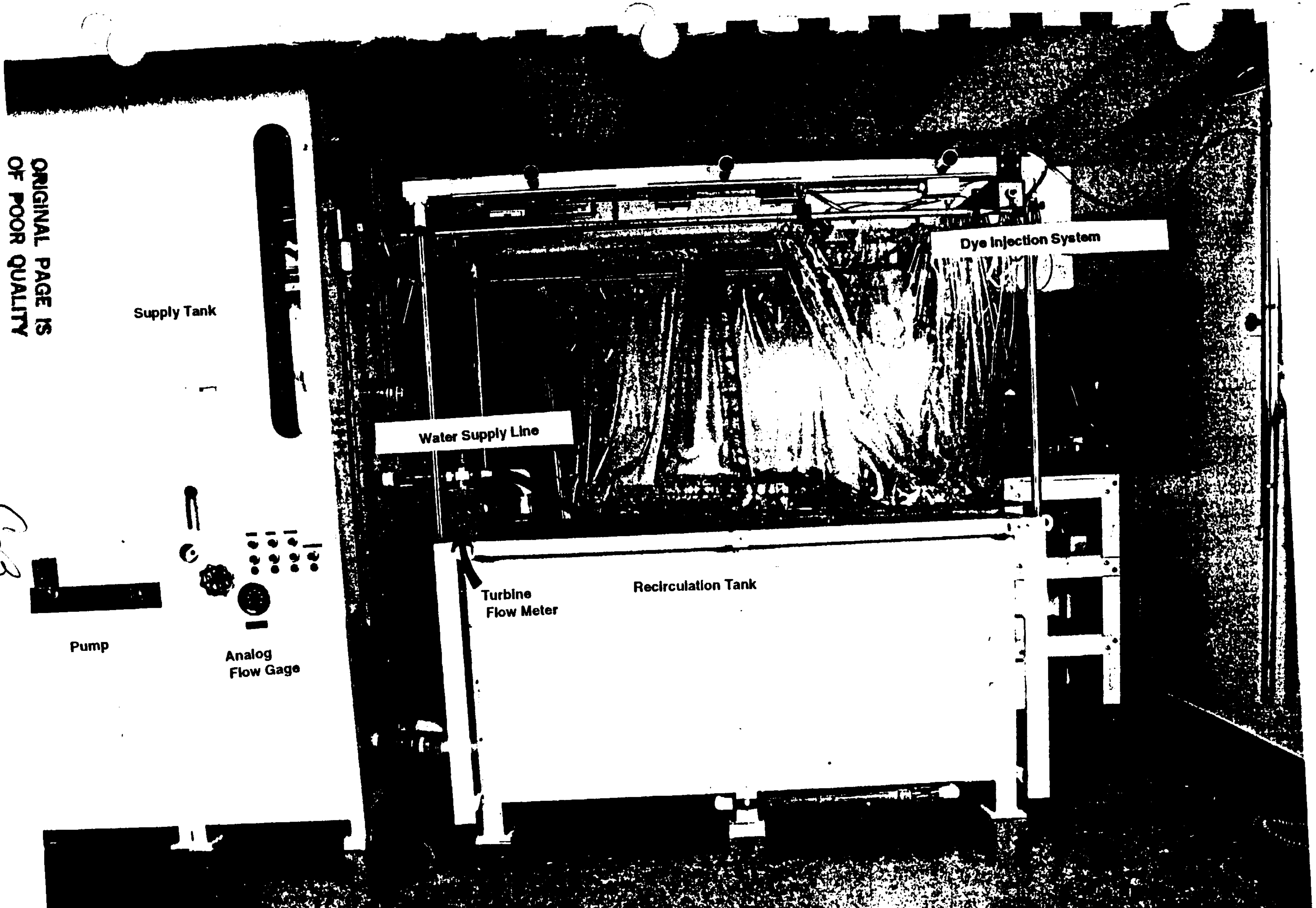
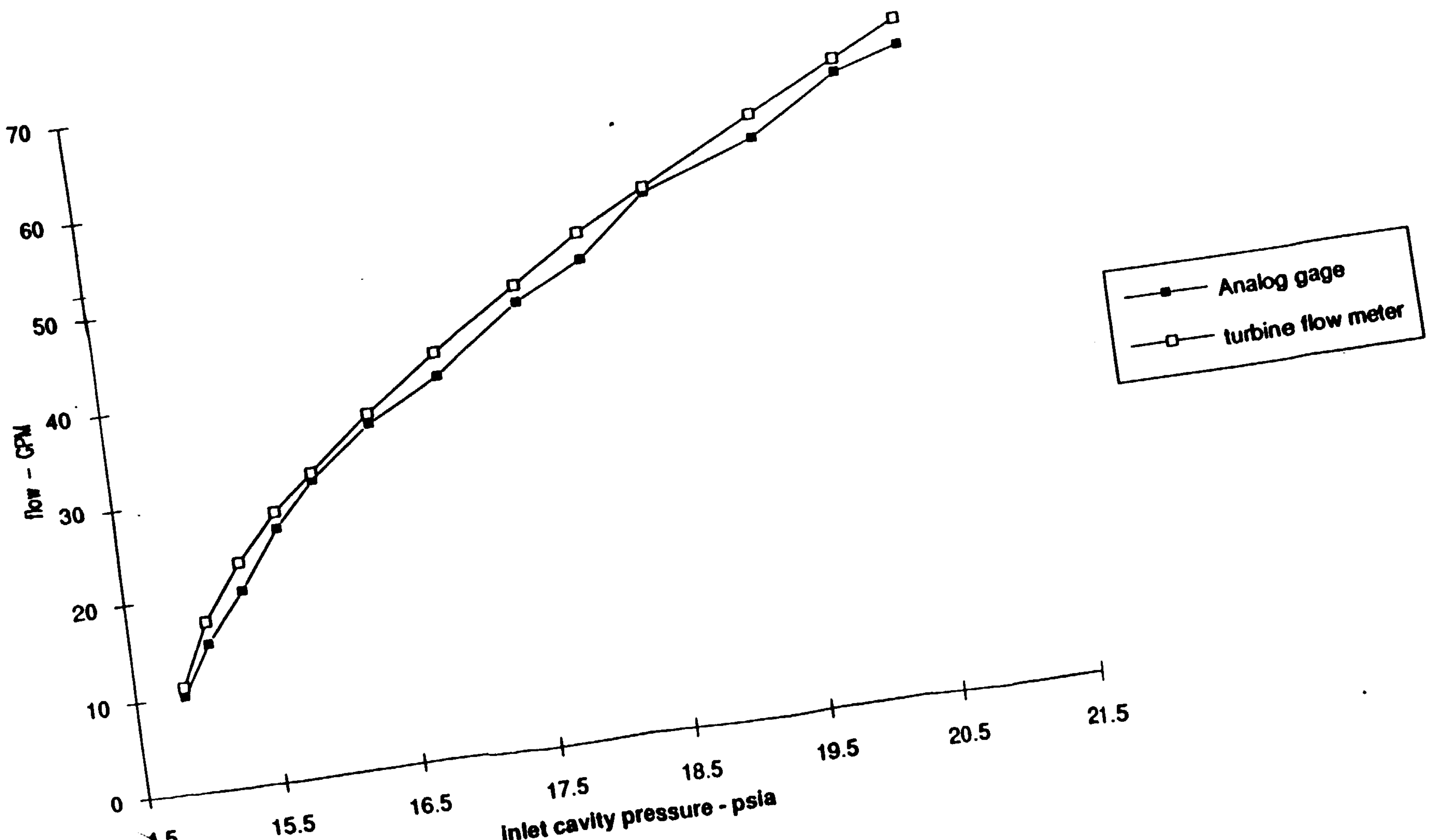


Figure IV-4 Water Table with Plexiglass Turbine Airfoil


70
60
50
40
30
20
10
0
flow - GPM
.5
15.5
16.5
17.5
18.5
19.5
20.5
21.5
Inlet cavity pressure - psia
Analog gage
turbine flow meter

tion 8/13/92

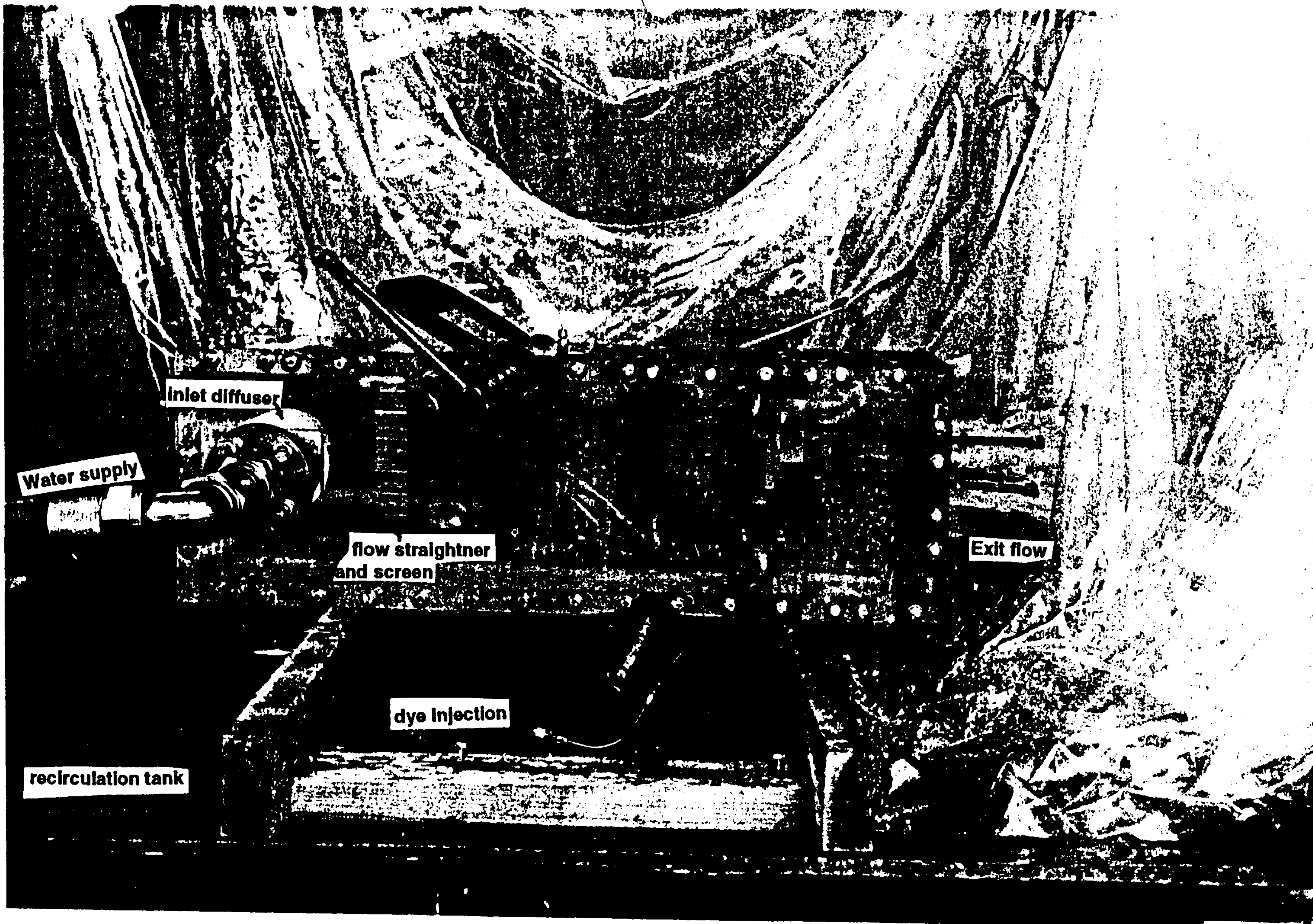


Figure IV-6 Picture of rig flowing on water table

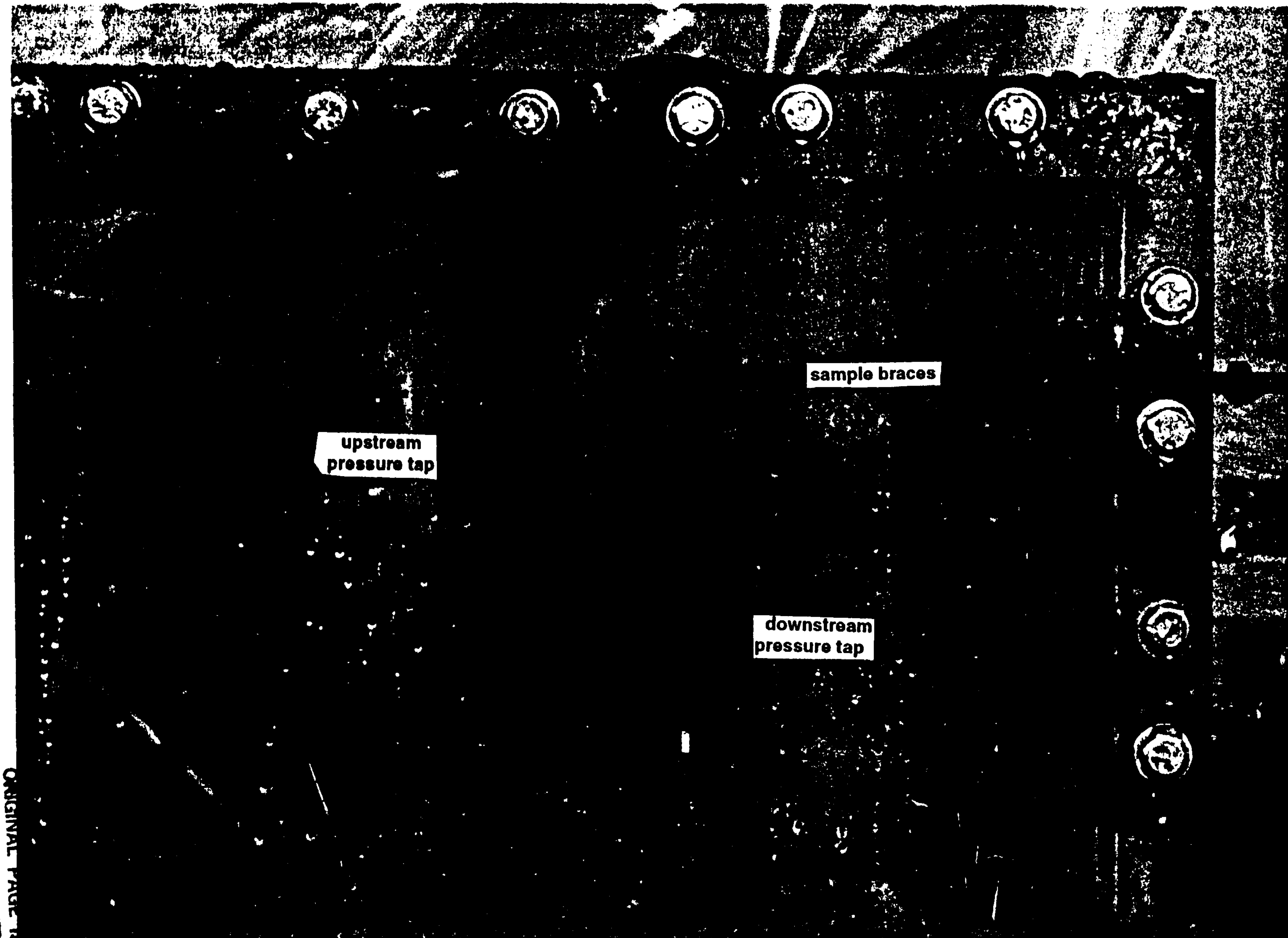
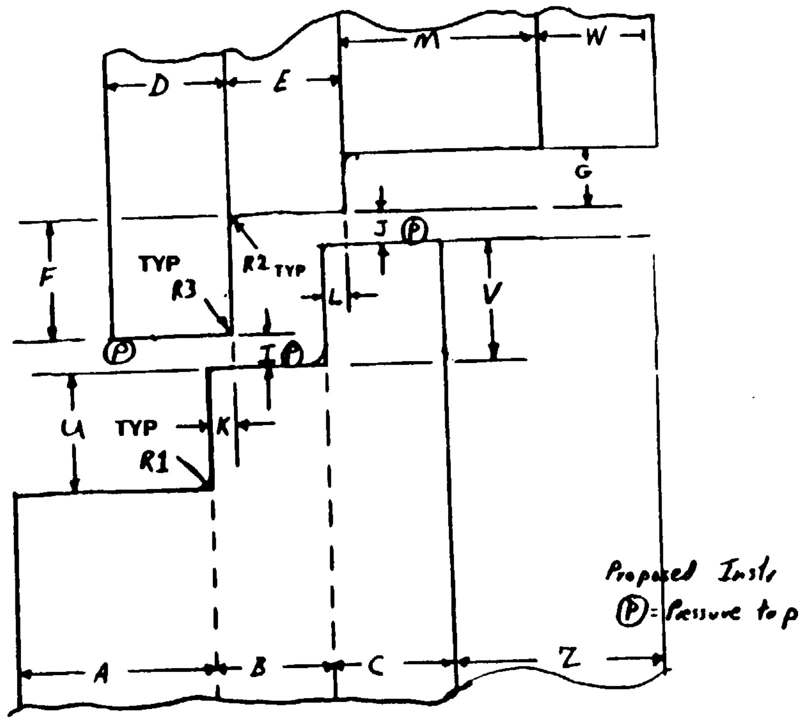


Figure IV-7 Side view picture of rig and test sample



I & J = 0.100 All Tests
K & L = 0.00 All Tests

				TAGUCHI SCOPE REDUCTION MATRIX								
VARIABLES	TEST # 1	TEST # 2	TEST # 3	TEST # 4	TEST # 5	TEST # 6	TEST # 7	TEST # 8	TEST # 9	TEST # 10	TEST # 11	TEST # 12
A = 0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625
B = 0.250 / 0.375	0.375	0.250	0.250	0.375	0.250	0.375	0.250	0.375	0.375	0.375	0.250	0.250
C = 0.250 / 0.375	0.375	0.250	0.250	0.250	0.375	0.375	0.375	0.250	0.375	0.250	0.250	0.375
D = 0.250 / 0.375	0.375	0.250	0.375	0.250	0.375	0.250	0.250	0.250	0.375	0.375	0.375	0.250
E = 0.250 / 0.375	0.375	0.250	0.375	0.250	0.250	0.375	0.250	0.375	0.250	0.250	0.375	0.375
F = 0.375 / 0.563	0.375	0.375	0.563	0.563	0.563	0.375	0.375	0.563	0.563	0.375	0.375	0.563
G = 0.188 / 0.375	0.188	0.375	0.188	0.188	0.375	0.375	0.188	0.375	0.375	0.188	0.375	0.188
M = 0.625 / 0.750	0.625	0.750	0.750	0.625	0.625	0.750	0.625	0.625	0.750	0.750	0.625	0.750
U = 0.200 / 0.375	0.375	0.375	0.200	0.200	0.375	0.200	0.200	0.375	0.200	0.375	0.200	0.375
V = 0.375 / 0.563	0.375	0.375	0.563	0.563	0.563	0.375	0.375	0.563	0.563	0.375	0.375	0.563
W = 0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
R1 = 0.131 / 0.200	0.131	0.131	0.131	0.131	0.131	0.131	0.200	0.200	0.200	0.200	0.200	0.200
R2 = 0.075 / 0.150	0.075	0.075	0.075	0.150	0.150	0.150	0.075	0.075	0.075	0.150	0.150	0.150
R3 = NOM / 0.075	NOM	NOM	0.075	NOM	0.075	0.075	0.075	0.075	NOM	0.075	NOM	NOM
Z = 0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625

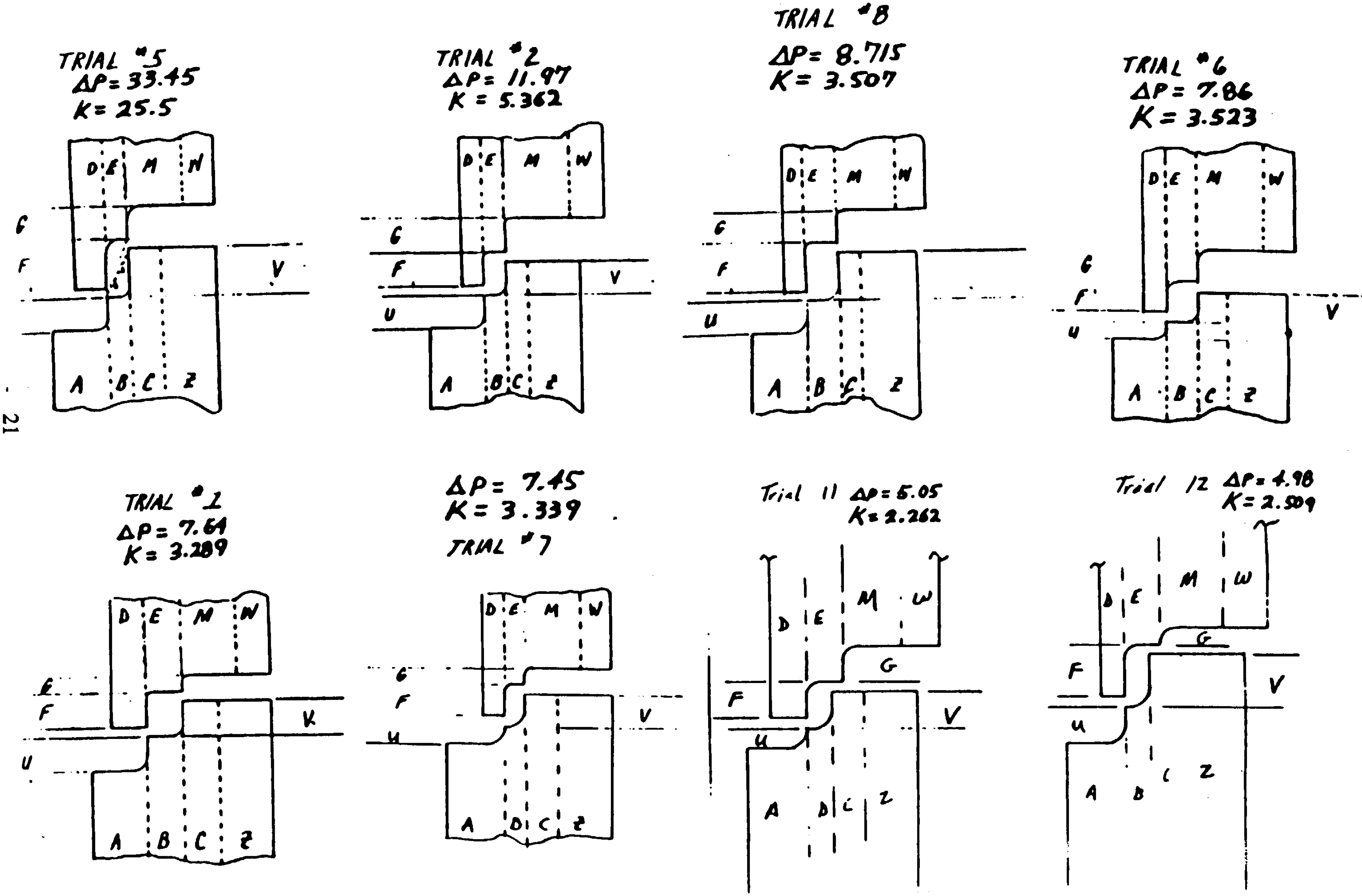
Figure V-1. Scope Reduction Taguchi Test Matrix

1	0.131	0.075	NOM	0.375	0.375	0.188	0.375	0.375	0.625	0.375	0.375		
0	0.200	0.150	0.075	0.200	0.563	0.375	0.250	0.250	0.750	0.250	0.250	Delta Pressure - psid	Flow - GPM
Trial	R1	R2	R3	U	V	G	D	E	M	B	C		
1	1	1	1	1	1	1	1	1	1	1	1	7.64	50
2	1	1	1	1	1	0	0	0	0	0	0	11.97	50
3	1	1	0	0	0	1	1	1	0	0	0	1.055	50
4	1	0	1	0	0	1	0	0	1	1	0	2.88	50
5	1	0	0	1	0	0	1	0	1	0	1	33.45	50
6	1	0	0	0	1	0	0	1	0	1	1	7.86	50
7	0	1	0	0	1	1	0	0	1	0	1	7.45	50
8	0	1	0	1	0	0	0	1	1	1	0	8.715	50
9	0	1	1	0	0	0	1	0	0	1	1	2.6	50
10	0	0	0	1	1	1	1	0	0	1	0	2.06	50
11	0	0	1	0	1	0	1	1	1	0	0	5.05	50
12	0	0	1	1	0	1	0	1	0	0	1	4.98	50
Delta P												95.71	600
Avg. "1's"	10.80917	6.571667	5.853333	11.46917	7.005	4.344167	8.6425	5.883333	10.86417	5.2925	10.66333		
Avg. "0's"	5.1425	9.38000	10.09833	4.48250	8.94667	11.60750	7.30917	10.06833	5.08750	10.65917	5.28833		
Differenc	5.666667	-2.80833	-4.245	6.986667	-1.94167	-7.26333	1.333333	-4.185	5.776667	-5.36667	5.375		
Rank	4th	9th	7th	2nd	10th	1st	11th	8th	3rd	6th	5th		

ORIGINAL PAGE IS
OF POOR QUALITY

Figure VI-4 Taguchi Scope Reduction Response Ranking Test Results

Figure VI-2 Taguchi Scope Reduction Test Sample Results Ordered by Delta P



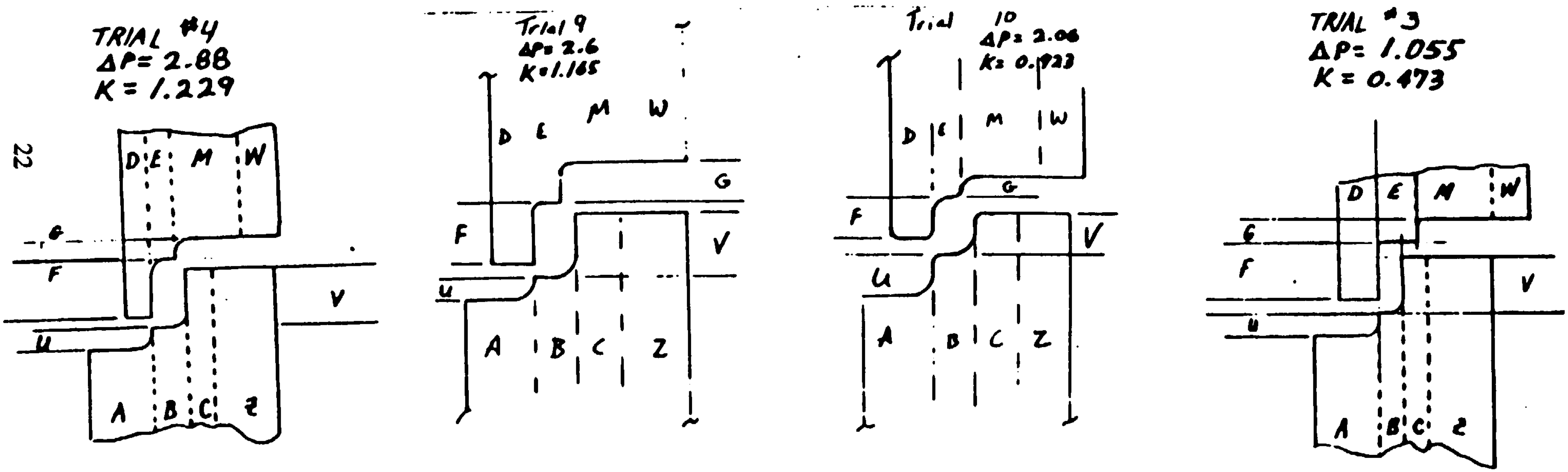
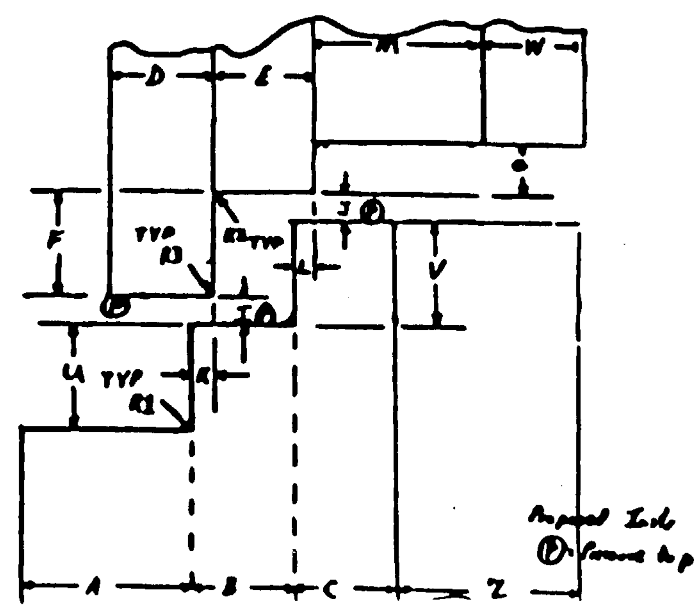


Figure VI-3 Taguchi Scope Reduction Test Sample Results Ordered by Delta P

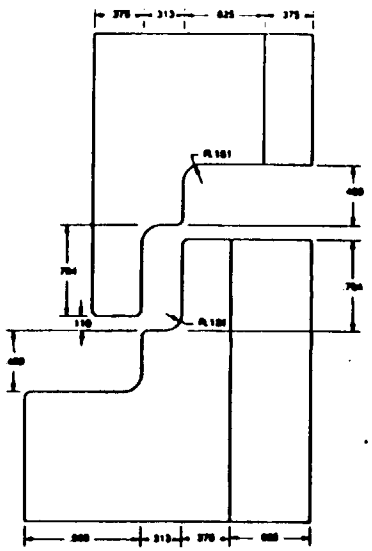
TAGL8OPT.XLS

				TAGUCHI OPTIMIZATION MATRIX				
VARIABLES	TEST # 1	TEST # 2	TEST # 3	TEST # 4	TEST # 5	TEST # 6	TEST # 7	TEST # 8
A = 0.9 (1" stock)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
B = 0.313/0.188	0.313	0.188	0.188	0.313	0.188	0.313	0.313	0.188
C = 0.375 (C+Z 1"st)	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
D=0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
E = 0.313/0.188	0.313	0.188	0.188	0.313	0.188	0.313	0.313	0.188
F = 0.704/0.422	0.704	0.422	0.704	0.422	0.704	0.422	0.704	0.422
G = 0.469/0.281	0.469	0.469	0.469	0.469	0.281	0.281	0.281	0.281
I=J = 0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
K=L = 0.0	0	0	0	0	0	0	0	0
M = 0.625 (M+W 1"st)	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625
U = 0.469/0.281	0.469	0.469	0.281	0.281	0.469	0.469	0.281	0.281
V = 0.704/0.422	0.704	0.422	0.704	0.422	0.704	0.422	0.704	0.422
W = 0.375 (M+W 1"st)	0.375	0.375	0.375	0.375	0.375	0.375	0.375	0.375
R1 = 0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131	0.131
R2 = 0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151	0.151
R3 = NOM	NOM	NOM	NOM	NOM	NOM	NOM	NOM	NOM
Z = 0.625 (C+Z 1" st)	0.625	0.625	0.625	0.625	0.625	0.625	0.625	0.625

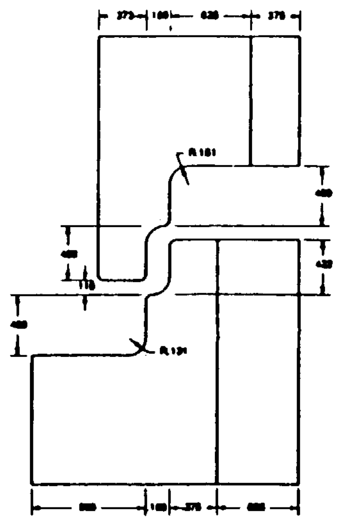
Figure VII-1 Taguchi Optimization Test Matrix



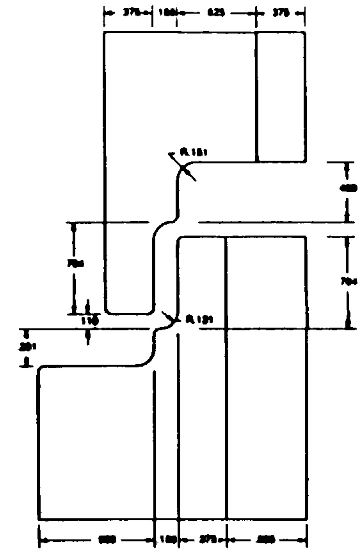
CONFIGURATION 1



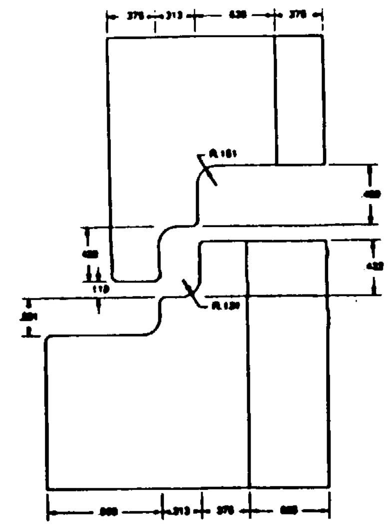
CONFIGURATION 2



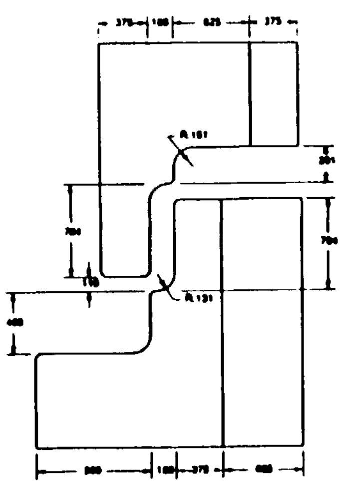
CONFIGURATION 3



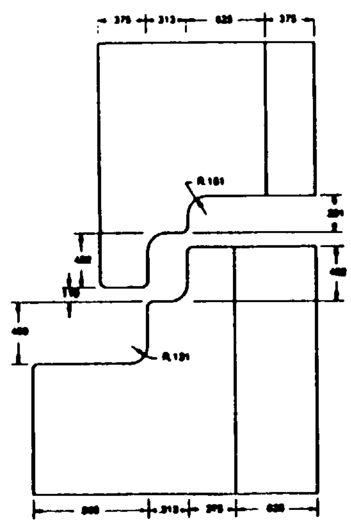
CONFIGURATION 4



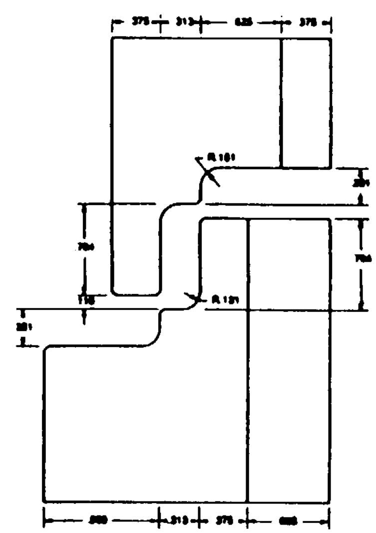
CONFIGURATION 5



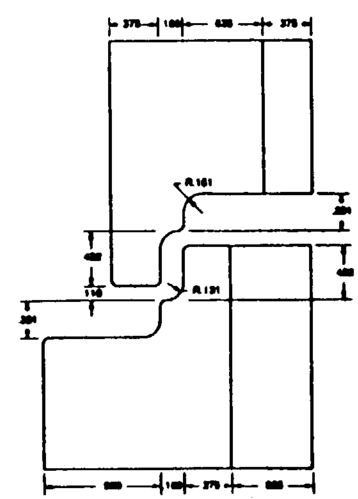
CONFIGURATION 6



CONFIGURATION 7



CONFIGURATION 8



CORNL8K.XLS

1	0.469	0.469	0	0.313	0.000	0.000	0.704		
0	0.281	0.281	0.000	0.188	0.000	0.000	0.422	line - on - line	
Trial	G	U	GU	B	GB	GV	V	K-loss	Flow - GPM
1	1	1	1	1	1	1	1	3.93	55.05
2	1	1	1	0	0	0	0	2.4375	55.1
3	1	0	0	1	1	0	0	2.886	55.155
4	1	0	0	0	0	1	1	3.5315	55.1
5	0	1	0	1	0	1	0	2.402	55.1
6	0	1	0	0	1	0	1	3.002	55
7	0	0	1	1	0	0	1	3.3835	55.075
8	0	0	1	0	1	1	0	4.0145	54.895
Delta P								25.587	440.475
Avg. "1's"	3.19625	2.942875	3.441375	3.150375	3.458125	3.4695	3.46175		
Avg. "0's"	3.2005	3.45388	2.95538	3.24638	2.93863	2.92725	2.93500		
Difference	-0.00425	-0.511	0.486	-0.096	0.5195	0.54225	0.52675		
Rank	7	4	5	6	3	1	2		

Figure VIII-1 Optimization Matrix Ranking by K-Loss Line-On-Line

1	0.469	0.469	0	0.313	0.000	0.000	0.704		
0	0.281	0.281	0.000	0.188	0.000	0.000	0.422	axailly open	
Trial	G	U	GU	B	GB	GV	V	K-loss	Flow - GPM
1	1	1	1	1	1	1	1	1.9815	55.05
2	1	1	1	0	0	0	0	1.665	55.075
3	1	0	0	1	1	0	0	2.3535	55.235
4	1	0	0	0	0	1	1	1.354	55
5	0	1	0	1	0	1	0	1.8685	55.05
6	0	1	0	0	1	0	1	2.0145	55
7	0	0	1	1	0	0	1	2.083	55.18
8	0	0	1	0	1	1	0	1.9355	55.085
								15.2555	440.675
Delta P									
Avg. "1's"	1.8385	1.882375	1.91625	2.071625	2.07125	1.784875	1.85825		
Avg. "0's"	1.975375	1.93150	1.89763	1.74225	1.74263	2.02900	1.95563		
Difference	-0.13688	-0.04912	0.018625	0.329375	0.328625	-0.24413	-0.09738		
Rank	4	6	7	1	2	3	5		

Figure VIII-2 Optimization Matrix Ranking by K-Loss Axially Open

CORNL8.XLS

1	0.469	0.469	0	0.313	0.000	0.000	0.704		
0	0.281	0.281	0.000	0.188	0.000	0.000	0.422	line - on - line	
Trial	G	U	GU	B	GB	GV	V	Delta Pressure - psid	Flow - GPM
1	1	1	1	1	1	1	1	7.615	55.05
2	1	1	1	0	0	0	0	4.895	55.1
3	1	0	0	1	1	0	0	5.5275	55.155
4	1	0	0	0	0	1	1	8.045	55.1
5	0	1	0	1	0	1	0	6.17	55.1
6	0	1	0	0	1	0	1	7.42	55
7	0	0	1	1	0	0	1	8.84	55.075
8	0	0	1	0	1	1	0	10.2375	54.895
Delta P								58.75	440.475
Avg. "1's"	6.520625	6.525	7.896875	7.038125	7.7	8.016875	7.98		
Avg. "0's"	8.166875	8.16250	6.79063	7.64938	6.98750	6.67063	6.70750		
Difference	-1.64625	-1.6375	1.10625	-0.61125	0.7125	1.34625	1.2725		
Rank	1	2	5	7	6	3	4		

Figure VIII-3 Optimization Ranking by ΔP Line-On-Line

CORNL8.XLS

1	0.469	0.469	0	0.313	0.000	0.000	0.704		
0	0.281	0.281	0.000	0.188	0.000	0.000	0.422	axially open	
Trial	G	U	GU	B	GB	GV	V	Delta Pressure - psid	Flow - GPM
1	1	1	1	1	1	1	1	2.76	55.05
2	1	1	1	0	0	0	0	2.4625	55.075
3	1	0	0	1	1	0	0	2.5725	55.235
4	1	0	0	0	0	1	1	2.65	55
5	0	1	0	1	0	1	0	2.46	55.05
6	0	1	0	0	1	0	1	2.835	55
7	0	0	1	1	0	0	1	3.1775	55.18
8	0	0	1	0	1	1	0	2.78	55.085
Delta P								21.6975	440.675
Avg. "1's"	2.61125	2.629375	2.795	2.7425	2.736875	2.6625	2.855625		
Avg. "0's"	2.813125	2.79500	2.62938	2.68188	2.68750	2.76188	2.56875		
Difference	-0.20188	-0.16563	0.165625	0.060625	0.049375	-0.09938	0.286875		
Rank	2	3	4	6	7	5	1		

Figure VIII-4 Optimization Ranking by ΔP Axially Open

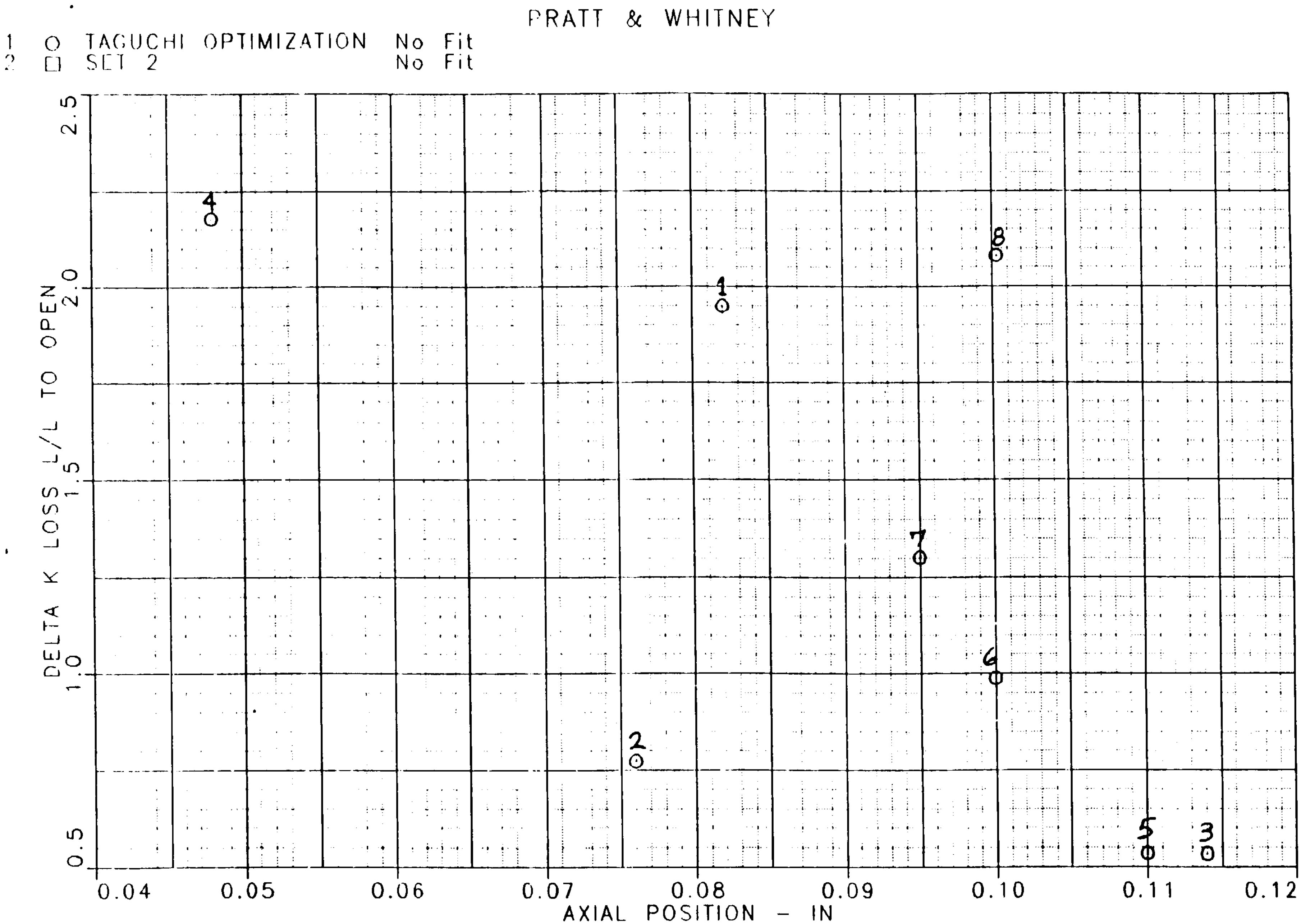


Figure VIII-5 Change in K-Loss of Samples

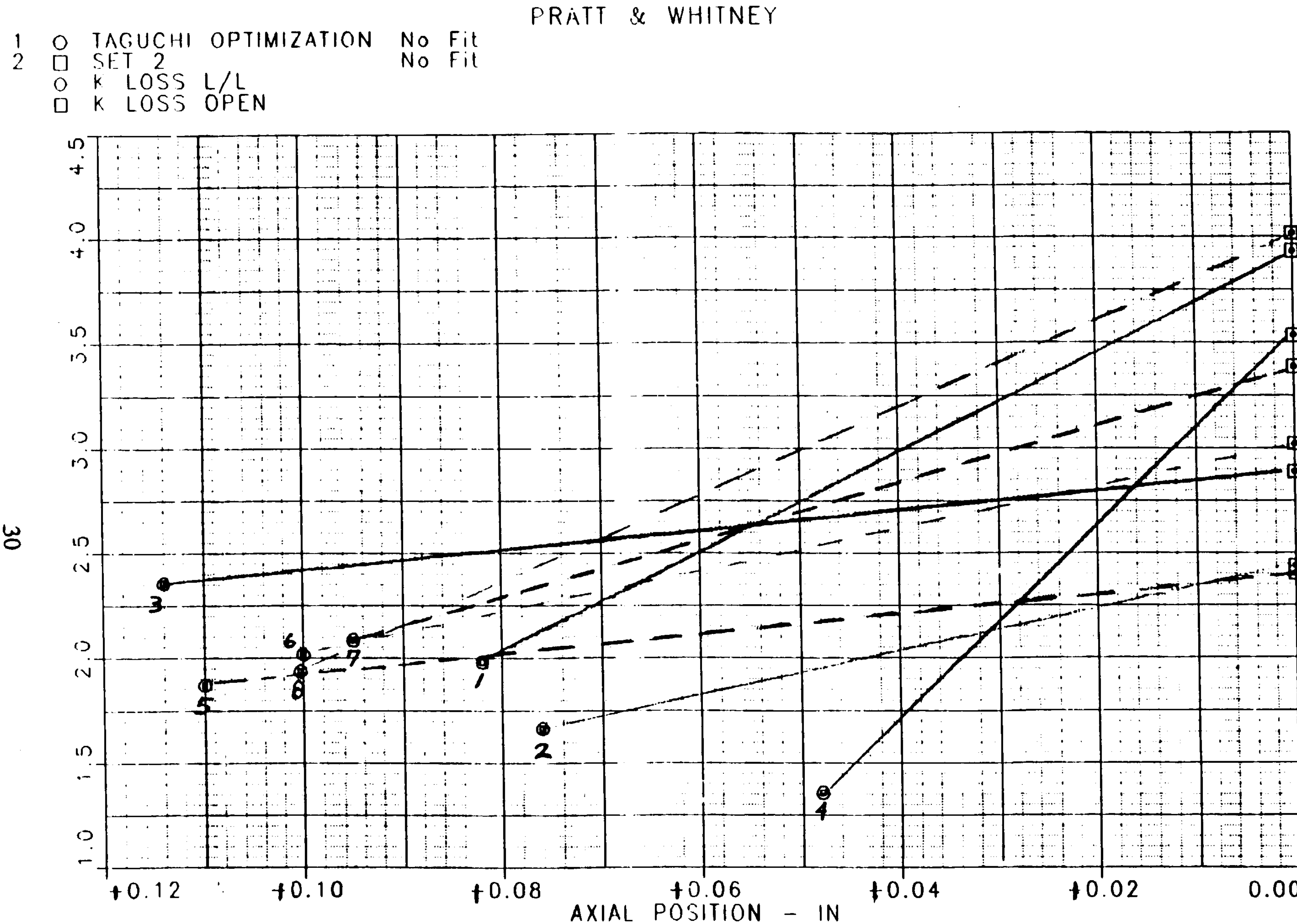


Figure VIII-6 Optimization Results K-Loss Change with Axial Position

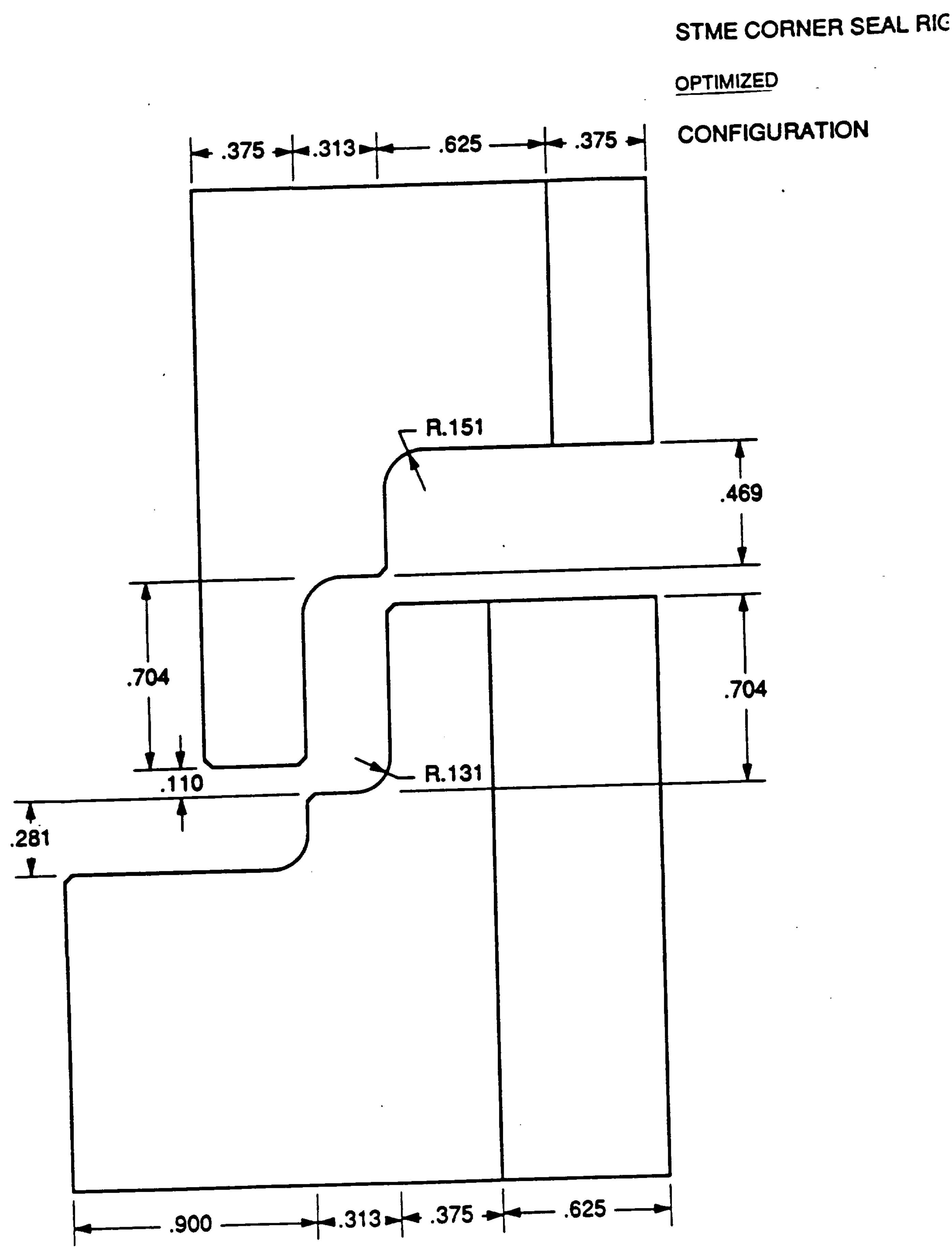


Figure IX-1 Optimized Sample

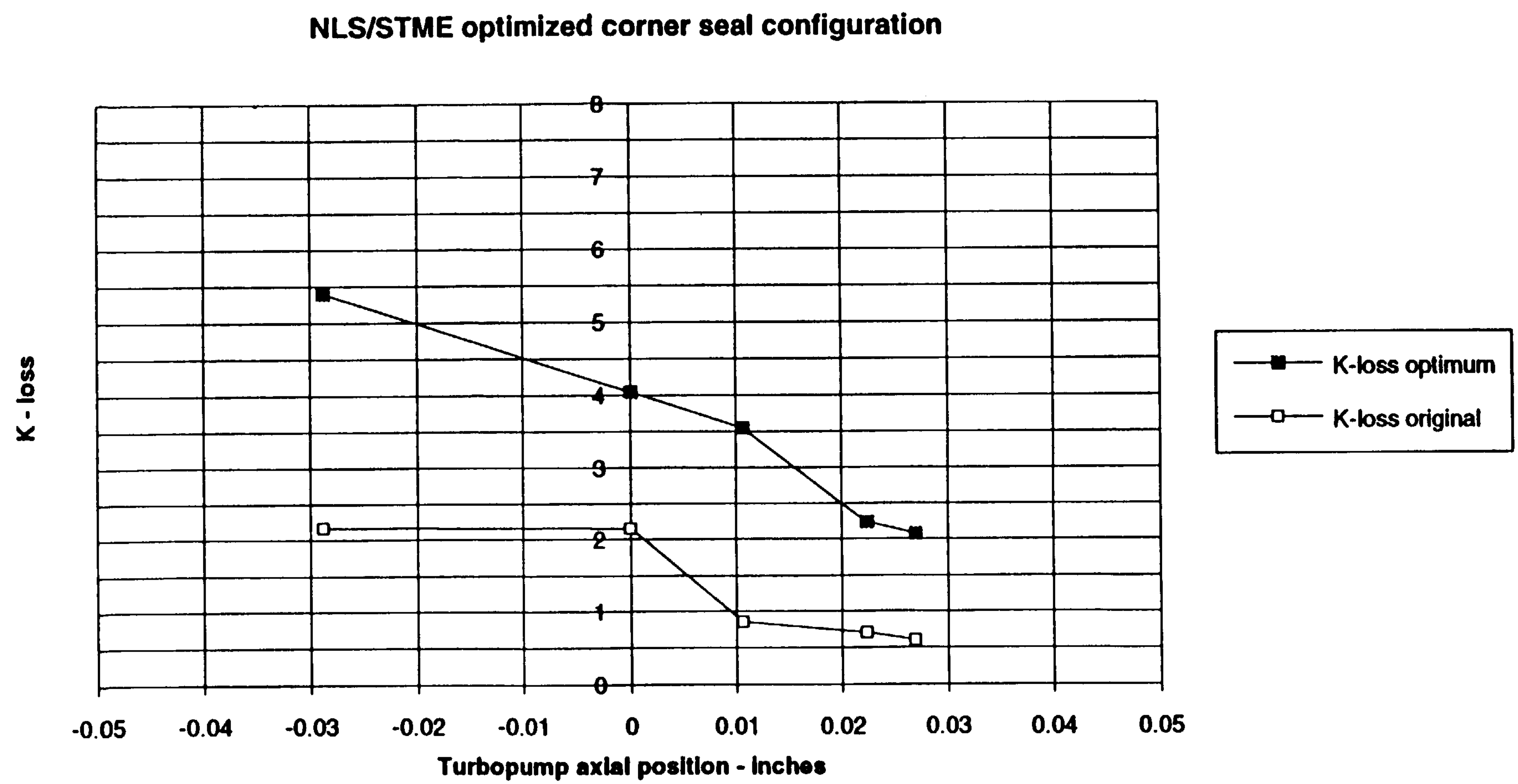


Figure IX-2 Characterization of Optimized Sample

Appendix A Calculations

water density (ρ) = 62.15 lbm/ft^3

mass flow (m) = Gal/min * 0.13368 ft^3/gal * 1 min/60 sec * 62.15 lbm/ft^3
(lbm/sec)

Area (A) = 8" * clearance gap * 144 ($feet^2$) line-on-line & overlap cases

Area (A) = 8" * SQRT(clearance gap^2 + axial $open^2$) * 144 ($feet^2$)
axially open case

gravitational constant (g_c) = 32.175 lbm-ft / lbf-sec^2

$K_{sys} = (\Delta P_{up\text{-}down} * 144. * 2. * g_c * \rho * A^2) / m$ (dimensionless)

3.0 PHASE I SEQUENCE OF EVENTS

The objectives of this program were to design and demonstrate high reliability approaches for a low life cycle cost and low recurring cost liquid oxygen (LOX) turbopump assembly, to validate the approach through design, fabrication, and test of prototype hardware and to develop a cost model applicable to production hardware. Reliability was to be a quantified design requirement in the same context as cost, performance, and weight.

Pratt & Whitney was to prepare a preliminary design of a liquid oxygen turbopump assembly including both pump and turbine consistent with the overall objectives of this program, as listed above, and the requirements listed in the Interface Design Requirements Document . The high reliability ideas studied included items such as reduction of failure modes and effects, application of materials characterized for the operating environment, simplified designs which minimized stress concentration, no welds, verifiable design criteria, and large margins on critical parameters. The emphasis of low recurring cost was intended to assure that the proper focus was placed on production cost, and operational cost including ease of inspection and minimum maintenance. Trade studies and analyses were conducted to identify the cost drivers and to evaluate and select those options best suited to achieving a low cost design. The preliminary design was based upon the best combination of the identified options.

In support of the preliminary design activity, trade studies, engineering analyses (material, structural, dynamic, thermal, rotordynamics, performance and flow), fabrication and process analyses, and laboratory tests to verify the viability of the candidate designs to meet cost, fabricability, performance and reliability goals were conducted. Historical turbopump reliability data was analyzed using statistical methods to provide a basis for the component reliability.

What follows are excerpts from the monthly reports that covered the individual studies, analyses, tests and reports performed during Phase I of this program.

July 1989

- Trade studies of various subcomponent configurations were initiated.
- Inertia weld demonstration on A-286 material was initiated. P&W is evaluating available tooling.
- Requests were initiated for casting stereolithography impeller in fine-grain Inco 718.
- Investigation began on the applicability of a diffusion bonding a shroud to a turbine integrally bladed rotor.
- An order was placed for cast Haynes 230 lab specimens.
- The Hazard Analysis and Failure Modes and Effects Analysis (FMEA) were initiated.
- Cost model definition began.
- The Technical Implementation Plan (DR-15) was completed and submitted.

August 1989

- Detailed trade studies of various subcomponent configurations continued.
- Material selection of major subassemblies is being conducted
- Interface load calculations were conducted to satisfy Interface Control Document (ICD) requirements
- Order for Cast Haynes 230 test bars was placed with Howmet-Hampton Div. in an effort to fully characterize this material
- PWA Space Shuttle Main Engine — Alternate Turbopump Development (SSME-ATD) Main Fuel Pump Housing tooling will be utilized for a casting demonstration of Haynes 230. This configuration is similar to

the housing geometry planned for the turbine inlet

- Cast impeller demonstration programs were initiated with both Howmet and Precision Castparts Corporation (PCC) corporations. Fine grain Inco 718 is the material planned for this demonstration

- A diffusion bonding demonstration program was initiated to evaluate the potential of bonding forged Waspaloy to cast MAR-M-247 for a bonded bladed ring application

- Additional materials (Waspaloy, Super A-286) were identified for inertia welding demonstrations. A Taguchi test matrix was developed to maximize demonstration effectiveness

- A request was initiated for Inco 718 powder metallurgy test specimens for material characterization

- Work continued on the Failure Modes and Effects Analysis (FMEA) and hazard analysis

- Cost model definition continued

- The Facility Plan (DR-04), Logic Network and Key Milestone Chart (DR-16), and Government-Furnished Property Management Plan (DR-06) were completed and submitted

September 1989

- Continued detailed trade studies of various subcomponent configurations continued. Conducted manufacturing and producibility design review to provide feedback for trade studies

- Placed order for stereolithography impeller section casting in fine grain INCO 718

- Initiated request for fabrication demonstration of cast-to-size turbine blades

- Received quote for INCO 718 powdered metallurgy test specimens. Reviewed supplier facility, set up demonstration test matrix

- Finalized Haynes 230 housing demonstration and INCO 718 impeller demonstration scheduled with supplier

- Material orders placed for diffusion bonding demonstration

- Hazard analysis and FMEA formulation continued

- Cost model definition continued.

- The Quality Plan (DR- 17), Material Control Plan (DR-23) and the System Safety Plan (DR-25) were completed and submitted.

October 1989

- Continued detailed trade studies of various subcomponent configurations. Design downselect was conducted on turbopump components

Coordination of suppliers efforts to develop innovative fabrication processes continued

  — Stereolithography processes for producing impeller plastic patterns being coordinated with suppliers

  — Wax pattern work has been initiated for a conventionally cast impeller and housing

  — Initiated activity with forging suppliers to evaluate a forged shaft and disk

  — Initiated activity on turbine blade castings

- Cost model review was held at P&W with Astronautics Lab personnel attending

  - Waspaloy was selected as an optional turbine housing material and will be characterized by Materials Engineering
  - GATORIZING® model program of turbine disk initiated
  - Defined turbopump purge cycle and submitted to Stennis for incorporation in their design requirements
  - Updated Interface Control Document (ICD), DR-28, and provided copies to MSFC, NSTL, and Rocketdyne
  - Responded to NASA questions regarding GFP plan, DR-06.
- Continued detailed trade studies of various subcomponent configurations.

November 1989

- Continued detailed trade studies of various subcomponent configurations
- Coordination of supplier efforts to develop innovative fabrication processes continued
  - — Space Shuttle Main Engine-Alternate Turbopump Development (SSME-ATD) pump inlet housing successfully cast in Haynes 230 material and currently undergoing material evaluation.
  - — Haynes 230 material lab specimens successfully cast and awaiting hot isostatic pressing (HIP) and heat treatment prior to shipping.
  - — Heat treatment evaluation of Haynes 230 conducted by P&W materials lab to confirm heat treat cycle selected.
  - — Stereolithography impeller plastics are being generated from a P&W SSME-ATD impeller model. The plastics will be used to form molds for an INCO 718 casting demonstration.

- — Two molds have been completed for an INCO 718 impeller conventional casting demonstration.
- — An additional INCO 718 impeller casting program has been initiated for purposes of spin testing at P&W.

- GATORIZING® model program demonstrated successful simulation of Waspaloy disk fabrication.

December 1989

- Continuing trade studies. Taguchi matrix identified main parameters effecting critical speed. The parameters are spring rate, overhang, and weight of inducer/impeller and rotor.

- Coordination of supplier efforts to develop innovative fabrication processes continued

  - — Powdered INCO 718 material received by Hypercon Corporation and chemistry is acceptable. Filling of fluid die with powdered material will commence.
  - — Initiated diffusion bonding demonstration with Textron Corporation to investigate diffusion bonding an impeller shroud configuration similar to the PW5000 hollow fan blade fabrication process.
  - — Stereolithography impeller section patterns were fabricated by Precision Castparts Corporation and will he used to fabricate more consumable casting molds. Molds used to cast 1/6 section impeller.
  - — Second Haynes '230 housing completed and undergoing nondestructive testing before finishing operations.
  - — Second INCO 718 impeller cast by Howmet is without visual flaws.
  - — Impeller design model being generated for Precision Castparts Corporation full-scale INCO 718

impeller casting demonstration.

  - Forging to be used for bi-cast impeller simulation demonstration was forwarded to Precision Castparts Corporation.

  - Haynes 230 test bars completed hot isostatic pressing and are undergoing heat treatment before shipment.

  - Inertia welded 4-inch diameter bar stock A286 in-house. Weld looks good, sample sent out to vendor for machining. Lab is to do tensile test and metallurgical evaluation when sample received from vendor.

- Preliminary hydrogen embrittlement testing indicated that Waspaloy may be a valid option for turbine housing material. Testing is continuing.

January 1990

- Continuing trade studies. Continued collecting data such as probability of vehicle loss, probability of launch delay, recovery and refurbishment man hours, unscheduled maintenance rate, cost, and performance for trade study down selection.

- Coordination of supplier efforts to develop innovative fabrication processes continued

  - Tooling fluid die design coordination meeting held with supplier to discuss computer simulation applications to the full-scale impeller powder metallurgy design task.

  - First iteration of stereolithography 1/6 INCO 718 impeller section molds have been prepared for casting. First casting scheduled for January

  - Second Haynes 230 turbopump housing visually shows indications of no fill in volute area due to rapid solidification. The next scheduled casting trial will use an insulated mold to avoid this problem.

- — Howmet impeller casting No. 1 was sectioned to evaluate material properties in the hub area. Results will be available in late January.
- — Initial nickel plating trials on the forged samples completed by supplier for bi-cast demonstration. Diffusion into parent material evident.
- — Haynes 230 test bars received at P&W for material characterization. Bars will undergo machining starting in January.
- — Continuing development of latest impeller design model for Precision Castparts Corporation full-scale INCO 718 impeller casting demonstration.
- — Working with supplier to demonstrate single shaft/disk. Trying to improve completion now scheduled for July 1990 because of tooling and extensive processing required.
- — Continuing effort of ordering cast impeller manufactured by stereolithography through casting technology program.

• DR-18 submitted during this period. Preliminary interface control document sent to Rocketdyne, Marshall, and Stennis.

February 1990

• Turbopump Design trade studies. Among items being traded are impeller surface profile, surface finish, and blade tolerance evaluated for performance and cost. Trades also include a separate thrust piston verses using the impeller backface for thrust balance. Alternatives being considered for the interpropellant seal are step seals, straight labyrinth seals, carbon seals, and brush seals.

• Fabrication processes:

— Pratt & Whitney is investigating several impeller fabrication techniques. One of these techniques involves the use of powder metallurgy. Test specimens of compacted INCO 718 powder are being provided by a supplier. Pratt & Whitney is assisting the supplier by degassing the powder. Screening of major processing parameters will be completed in February. Specimens will be available for testing in March.

— Conventionally cast impellers are also being demonstrated. One impeller uses existing industrial tooling similar to our design and another uses dedicated tooling that specifically represents our design. Fine grain has been demonstrated using the industrial tooling.

— Another demonstration process is using stereolithography. Two INCO 718 impeller samples have been successfully cast using stereolithography. Both casting show minor local material shrinkage.

— Fabrication demonstration of a full-size impeller from stereolithography through the Casting Technology Program has started. A mismatch between the airfoils and hub that results from curing is being addressed by a process intended to maintain geometry of the airfoils during curing.

— Bi-casting, another impeller fabrication consideration, casts INCO 718 onto a forged bar forming a metallurgical bond.

— Pratt & Whitney's Materials Engineering and Technology laboratory is diffusion bonding INCO 718 sheet to forged INCO 718 test bars to determine the process pressure and temperature parameter ranges before supplier activity begins. The purpose is to simulate bonding of a shroud to a forged open face impeller.

— The ceramic shells for casting of Haynes 230 housing numbers 3 and 4 have been completed, casting is scheduled for February.

— Machined Haynes 230 test bars are in-house for material property testing. Tensile and low-cycle fatigue testing in air and hydrogen started the last week of January.

— Polymer samples, a lightweight material under consideration, are being machined for LOX compatibility and tensile testing.

March 1990

- Turbopump Design trade studies. Among items being traded are impeller surface profile, surface finish, and blade tolerance evaluated for performance and cost.

  — Performed internal flow analysis and analyzed thrust load capability for the latest liquid oxygen (LOX) pump configurations. Leakage flow rates, pressure, and temperature distribution were analyzed in a study of four interpropellant seal (IPS) packages. The IPS packages being considered in the trades are stepped labyrinth seal, straight through labyrinth seal, carbon seal, and brush seal. A separate thrust piston was traded against an impeller thrust-piston. Particular attention was directed toward the study of thrust load capability, hydrogen supply availability, and axial thrust load balance.

  — Three of the four pump cross-section used for the trade studies have been weighted. Weight estimates have been broken down by major component. Weight estimate for the final cross-section is in progress.

  — Currently investigating various positive closure seal concepts. Secondary flow analysis estimates a lift-off seal would reduce He flow to approximately 0.00026 PPS compared to 0.106 PPS for the stepped seals.

  — Data is being compiled for design trade studies. Components being traded include turbine blades, impeller, bearings, shaft/disk, thrust piston, and interpropellant seal packages. Preparing to review configuration selection comparison sheets with NASA by telephone conference.

  — Responded to questions from the Astronautics laboratory's design review of Pratt & Whitney's (P&W) design update presentation to NASA last December.

— reports and design studies conducted in support of the LOX turbopump design are being compiled for submittal to NASA.

— Design considerations and verification tasks being fed to the failure mode and effects analysis on a continuing basis.

— Casting supplier reviewed the structural housing configuration with P&W design personnel and suggested various casting features to improve pouring process and yield. The casting supplier's suggestions are being incorporated into the housing designs.

• Fabrication processes:

— Cast Impellers

A third full-scale fine grain INCO 718 impeller has been cast using existing industrial tooling. Following mold removal, visual inspection revealed no flaw indications. The part is presently undergoing hot isostatic press (HIP)/heat treatment prior to nondestructive testing (NDT) evaluation.

A stereolithography fine grain INCO 718 1/6 impeller section sample has been macro-etched for display purposes. A second casting will undergo full HIP/heat treatment for material evaluation.

A second set of airfoils for the full-scale stereolithography impeller did not mate properly with the hub and shroud. The CAD profile used for machining the hub and shroud will be incorporated into the stereolithography profile files to ensure the correct profile is used (i.e., match the hub). In addition, the program now has access to a larger stereolithography apparatus which will allow parallel development of a full-size stereolithography impeller pattern.

— Powder Metal

Rapid Omnidirectional Compaction (ROC) Powder Metallurgy INCO 718 specimens are being evaluated for optimum parameter selection. Test specimens of selected compaction temperature and degas conditions are currently undergoing metallurgical characterization.

Initial results indicate high compaction density with some desirable microstructure characteristics.

Additional testing is underway to determine chemistry, specific density, and heat treatment requirements.

Parameter selection will be made for the next step of the powder evaluation.

— Bi-Casting

Two iterations of the INCO 718 Bi-cast program have been completed.

Iteration No. 1 achieved some local area bonding, and provided a base for parameter evaluation.

Iteration No. 2 achieved a consistent bond along with an increase in bond area.

Investigation will continue in attempts to increase diffusion across the bond and achieve 100 percent bond area.

A full material characterization is underway.

— Diffusion— Bonding

Initial INCO 718/INCO 718 diffusion bond trails have been completed, and are being metallurgically evaluated. Additional samples will be fabricated using a Ni-foil interface to determine the foil's influence on diffusion.

— Housing

A third Haynes 230 housing casting has been completed with altered pour temperature. Preliminary visual indications show no flaws.

— Inertia Welding

Teledyne has completed the super A286/A286 forgings and the material is enroute to P&W.

The inertia bonding Taguchi study will commence following the machining of this material.

• Laboratory testing

— Initial Haynes 230 tensile testing in air and hydrogen atmospheres has been completed. Evaluation of testing and report documentation is underway. Fatigue testing will begin this month.

— Castable Waspaloy was also tested in air and hydrogen atmospheres. The tensile tests have been completed, the low-cycle fatigue (LCF) tests will begin this month.

— Tensile and LCF tests of light weight thermoplastics in cryogenic conditions will be completed next month.

April 1990

• Design Activities

Configuration comparison sheets containing engineering weighting factors for design downselect were reviewed with NASA-MSFC by telephone conference on March 21, 1990. This action was a milestone requirement. Six trade studies were reviewed including impeller, turbine housings, shaft/disk, bearings, and one/two stage turbine. Factors for technical risk assessment were also discussed. Responses are currently being generated for the action items from the telecon. Configuration comparison sheets are being completed for the interpropellant seal, thrust piston, and airfoils.

Vane profiles and a flowpath contour for the impeller have been completed. The airfoil definition has been incorporated into a three dimensional impeller model, and the CAD file will be forwarded to the casting supplier for fabrication of a full-scale impeller casting.

Internal flow analysis for separate thrust piston and impeller/thrust piston concepts has been updated to reflect the current definition. Leakage flowrates and pressure/temperature distribution are being analyzed. Particular attention is being focused on thrust load capability, hydrogen supply availability, liquid oxygen (LOX) recirculated flow rates, and axial thrust balance.

Design consideration and verification tasks are being fed to Failure Mode and Effects analysis on a continuing basis.

Reliability is evaluating turbine housings taking into consideration the side load impact on bearing life and related operations costs.

- Fabrication Processes

— Impeller Technology

Diffusion Bonding

Sample No. 1 of the Gatorizable Waspaloy samples has been computed. The fine-grain characteristics of Gatorizable Waspaloy provides high ductility that aids the diffusion bonding process.

Although some bonding was achieved, there were significant areas of no-bond. .An electropolishing technique used on the bonding surfaces prior to processing was determined to be the problem. Corrective action has been taken, and the second iteration will be attempted in the near term. .Metallographic evaluation of [Iteration .No. 1 is continuing.

Bi-Cast

Sample No. 3 was completed, but a bond was not achieved. Oxidation on the Ni- plating surfaces was observed and inadequate plating thickness was attributed to the lack of bond.

A plating thickness of 0.0005 inches was used to obtain data on minimum allowable plating thickness. Previous trials had used a thickness of 0.002 inches.

The next trial will be conducted in a vacuum furnace to minimize oxidation and the related effects. In addition, two variations in plating thickness will he attempted, 0.001 and 0.002 sample without plating will also he attempted.

Rapid Omnidirectional Compaction

Preliminary results of the material screening indicate that all Rapid Omnidirectional Compaction (ROC) Inconel (INCO) 718 samples have 100 percent density per the specified density of INC0 718. Metallurgical evaluation is continuing. Currently, the test pieces are undergoing gradient furnace heat treatment to determine the optimum set of processing parameters. These parameters will be used in producing powder for mechanical property evaluations.

— Structural Housings

Waspaloy

A Request for Quotation (RFQ) to the casting supplier has been initiated for the purpose of demonstrating a structural housing with weldable Waspaloy. Waspaloy is being considered as a material for the turbine housings on the oxygen pump, and has been screened by Pratt & Whitney for use in hydrogen environments.

Haynes 230

The Haynes 230 turbine housing evaluation is continuing. The third housing is currently undergoing hot isostatic pressing (HIP)/ heat treatment processing prior to nondestructive testing evaluation. In addition, wax pattern generation for Trial No. 4 has been initiated. A decision will be made regarding the need for additional trials following Trial No. 4.

—One Piece Shaft/Disk

Pratt & Whitney has received marked-up prints from the forging supplier for review and approval regarding the forging geometry specification. Following approval of these prints, tooling fabrication will commence.

—Cast to Size Blades

This task is being requoted by the casting supplier because of potential technical problems with the initially quoted casting method.

- Laboratory Testing

— INCO 718

An investigation has been initiated to determine the applicability of cast INC0 218 to low-pressure hydrogen environments (i.e. under 1000 psia). Preliminary data from Waspaloy testing indicates that mechanical property degradation are less severe at lower pressures.

— Thermoplastics

Torlon, a lightweight thermoplastic, is being considered for a pump inducer application. Liquid oxygen compatibility impact testing, and mechanical property cryogenic tests are continuing to determine the optimum grade of torlon for this application.

May 1990

- Design Activities

On April 24, 1990 the Advanced Development Program Liquid Oxygen Turbopump Configuration Selection presentation was conducted at Marshall Space Flight Center. The selected cross-section for preliminary design was discussed along with supporting technical data for rotordynamics, hydrodynamics, aerodynamics, and internal flow. Hardware fabrication tasks were also reviewed. The presentation was a milestone requirement that concludes the trade studies. Responses are currently being generated for the action items and comments from the presentation. Where applicable, comments and action items are being considered for incorporation into the preliminary design. As a result of one of the action items. rotordynamics has completed an analysis to determine the sensitivity of rotor instability to increases and decreases of inducer/impeller weight.

Preliminary three-dimensional computer models were created for both the impeller and inducer. The impeller CAD file has been forwarded to the casting vendor for full-scale impeller casting trials. Castings will be evaluated by spin testing and metallurgical examination.

Evaluations of the design cross-section are being conducted with manufacturing, assembly, and casting vendors for input into the preliminary design layouts. Similar efforts for instrumentation input will be addressed up front in the preliminary design.

Failure Mode and Effects Analysis is being updated to reflect the selected configuration.

- Fabrication Processes

  - Impeller Technology

Precision Cast

The third fine-grain Inconel 718 impeller casting was displayed at the ADP Conference, and has been returned to the Howmet Corporation for final heat treatment and nondestructive testing. Delivery of this casting will mark the completion of the Impeller Demonstration Program. Mechanical property testing and metallographic evaluation will continue at Pratt Whitney.

Rapid Omnidirectional Compaction (ROC)

Metallurgical evaluation of the heat treated ROC samples has been completed. A fine-grain wrought microstructure has been achieved, and optimal processing parameters have been selected. Preliminary mechanical property data will be collected from smooth tensile specimens currently being machined. Geometry studies using the parameters selected will begin in May.

Bi-Cast

Trials 4, o, and 6 have recently been cast, but have not been evaluated for bonding. The trials, poured in a vacuum furnace, will determine the minimum required plating thickness to prevent oxidation of the forged material. Evaluation of bonding will begin following delivery of specimens to Pratt & Whitney in May.

Stereolithography Castings

The second of two fine-grain Inconel 718 castings was received from Precision Castparts Corporation. This part was processed through hot isostatic press (HIP) and heat treat, and will undergo material evaluation at Pratt & Whitney.

—One piece shaft/disk

The supplier has completed tooling fabrication and is currently preparing for extrusion inlay.

—Haynes 230 Weld Program

Two L16 Taguchi matrices were conducted for Haynes 230 dimple and through-going welds. Cast Haynes 230 stepblocks were used for the study, and preliminary fluorescent penetrant inspection (FPI) results indicate no major difficulties in welding the material. The Haynes i30 pump housing demonstration piece No. 2 will be used to verify the selected welding parameters in an actual component configuration.

- Laboratory Testing

—Torlon

A grade of the poly-amide-imide, Torlon, has passed the LOX compatibility impact test. Initial test results indicated 0 failures in 20 attempts. The test will be repeated to verify these results. If successful, mechanical property testing will follow.

—Haynes 242

Smooth Tensile testing on cast Haynes 242 is being conducted in hydrogen to screen the material for potential turbine applications.

— Stellite 31

Cast Stellite 31 material samples have been obtained for material property screening in hydrogen. Based on these results, this material may be considered for turbine housing applications.

June 1990

- Design Activities

Design activities were initiated for preliminary design of the ADP Oxygen Turbopump. An attempt to incorporate the latest STEP design cycle into the preliminary design is underway. Hydrodynamic and aerodynamic cycle iterations are currently being conducted in an effort to finalize this cycle. Schedule milestones were established for the design layouts of the major turbopump components (inducer/impeller, housings, interpropellant seal (IPS), shaft/disk, blades, vanes, and bearings). Responses are being generated for the action items and comments from the configuration selection.

— Test Impeller

A two-dimensional (2-D) nodal structural analysis (NASTRAN) model of the test impeller has been completed, and a three-dimensional (3-D) model has been initiated. Impeller CAD files defining the blade and flowpath profiles were delivered to the casting vendor. Vendor recommendations to improve the castings were incorporated into the preliminary impeller/casting sketch.

— Blades and Vanes

Turbine flowpath and elevations are being defined for the preliminary design cycle. The turbine module features a two-stage disk with common dovetail broach slot and common airfoils with tip shrouds and hollow core. A one-dimensional, thermal-shock analysis was performed on the turbine hot flowpath hardware to identify maximum wall thickness limits for the turbine blades and vanes. Turbine durability guidelines were established for ADP Oxygen Turbopump aerodynamic design which will improve the thermal-shock characteristics of the design. The guidelines set dimensional limits for leading and trailing edge diameters from root to tip, wall thickness taper, and core diameters.

— Turbine Housings

A preliminary linear-elastic analysis for the turbine housing has been performed. A 3-D model of the backbone structure that connects the pump housing to turbine inlet and exit housing is being used for in-depth analyses. Particular attention was focused on reducing the stress field around the cut-out area for the inlet volute and maintaining concentric flange diameters for tip clearance control.

— Inducer/Impeller

A 3-D NASTRAN model of both the inducer and impeller for low-cycle fatigue (LCF) and Fracture Mechanics analysis is being constructed. The design will be optimized for minimum weight to provide additional critical speed margin.

— Reliability, Maintainability, and Safety

Maintainability design criteria/considerations were updated to reflect the selected configuration. The design criteria encompasses assembly/disassembly, inspection, engine interface, and health monitoring system. Reliability is revising the FMEA and developing a critical parts list.

- Fabrication Processes

  — Impeller Technology

  Precision Casting

  Precision Castparts Corporation (PCC) has received the full-scale ADP impeller model, and tooling orders are being initiated. The full-scale fine-grain Inconel 718 test impeller will be produced during the remaining time in Phase I and will undergo spin testing to verify structural integrity of the impeller casting.

  Rapid Omnidirectional Compaction (ROC)

  Preliminary Mechanical Property testing indicates that the tensile properties of the ROC Inconel 718 are promising. Although only limited testing has been performed, the data illustrates that a fine-grain wrought Inconel 718 micro-structure can be achieved with this process. Details regarding geometry studies for the remainder of Phase I are being finalized. The geometrical shapes produced will be used to anchor an analytical model which will determine fluid die requirements for producing net-shape hardware.

  — One Piece Shaft/Disk

  The extrusion of two Waspaloy one piece shaft/disk forgings has been completed by the forging supplier. The preliminary results indicate success, and no visual flaws were reported. Metallography and Mechanical Property testing will follow.

  An additional demonstration of the one piece shaft/disk using A286 material is being pursued. A286 is a material candidate for the shaft/disk configuration, and the fabrication demonstration/analysis will provide material property data required to substantiate this design.

— Structural Castings

Preliminary test results of cast Haynes 242 material shows that the material is an excellent candidate for the Turbine Housing application. A casting demonstration in a structural housing configuration is being pursued to evaluate the castability of the alloy in a complex geometry. Additionally, cast Haynes 242 plate stock will be obtained for additional material characterization.

• Material Testing

—Torlon

The second iteration of Lox Compatibility Testing has been completed for Torlon. The testing was a success with 0 failures/20 attempts. As both iterations of testing have been successful, additional material characterization will be pursued.

July 1990

• Design Activities

In June design activities continued toward generating layouts for the preliminary design of the LOX Turbopump The latest cross section has incorporated a one-piece shaft/disk in lieu of the bolted configuration This design provides an increased critical speed margin at the turbine end and lower production cost over the bolted configuration. Two (2) one-piece shaft/disk forgings will be demonstrated at a forging vendor to substantiate the design.

— Test Impeller

Structures has run the 2D NASTRAN model of the test impeller and is finalizing the 3D model. Assembly tooling has generated a preliminary arbor tooling design and is coordinating with mechanical design to define the interface fits and balance features. The arbor tooling is being designed to be reusable and capable of spin testing in a cryogenic atmosphere.

— Blades and Vanes

Design has provided the casting vendor a sketch of the blade root configuration for the cast-to-size blade fabrication task. Vibration analysis was initiated for the turbine blades and vanes.

IN 100 is being considered as a blade material. 1N 100 has a lower density than MAR-M-247 which provides a structural advantage over the MAR-M-247 and, IN 100 has slightly lower material cost when compared to IN 100.

Rim pulls were calculated for the new airfoil cross section and the turbine disk has been resized accordingly. Turbine durability has set the blade core definition along with dimensional guidelines for the shroud.

— Turbine Housings

Structures has completed initial 3D evaluation of two potential forging materials (Haynes 242 and Incoloy 909) for the backbone structure that connects the pump housing to the turbine inlet and exit housings. Results indicate that both materials have positive safety margins for all areas of the backbone. Design is modifying the cast material configuration to meet structural requirements.

Aerodynamics has resized the inlet and exit volutes for the new design cycle.

— Inducer/Impeller

Based on preliminary 2D .NASTRAN model results, design is iterating the inducer and impeller design to reduce weight from each component. PWA 658 is being considered as an inducer material to reduce weight that improves pump end critical speed. Pratt & Whitney (P&W) will screen material specimens for LOX compatibility with a mechanical impact test at ambient pressure.

— Reliability, Maintainability, and Safety

Reliability had developed a critical parts list for the .ADP LOX Turbopump component that identifies failure modes and the probable cause.

- Fabrication Processes

  — Impeller Technology

  The third full-scale fine-grain Inconel 718 impeller which was cast with existing tooling is scheduled to be finished with (HIP)/heat treatment and nondestructive testing (NDT) evaluation in early July. The impeller will he returned to P&W for further NDT.

  PCC is continuing with procurement of the cast full-scale impeller tooling. Three full-scale fine grain Inconel 718 test impellers will be fabricated and one will undergo spin testing to verify structural integrity of the impeller casting.

  Rapid Omnidirectional Compaction (ROC)

  Several of the fluid dies for the remaining Inconel 718 ROC trials have been received by Hypercon Corporation. The remaining trials will include five different geometrically shaped dies. The dies will give dimensional and material property data needed to further analyze the process and produce net shape hardware. These trials are expected to be finished by mid-July .

  — One-Piece Shaft/Disk

  Material property testing is being initiated at Cameron on the Waspaloy one-piece shaft/disk. Pratt & Whitney will conduct mechanical property testing after receiving Waspaloy parts in late .July.

  Progress is underway in the fabrication a one piece shaft/disk using A286 material. 'This fabrication is scheduled for completion at the end of Phase 1, analysis completion is planned for early Phase 11.

— Structural Castings

The casting demonstration of a Haynes 242 structural housing is being initiated with Howmet to determine the castibility of this alloy in a complex part. This demonstration will use existing tooling for low cost. The program will also provide Haynes 242 cast plates for additional material characterization.

Haynes 242 alloy has been received and the structural dies are scheduled to be at Howmet by the end of July. This demonstration is expected to run through the end of July.

— Bi-Casting

Three more trials have been completed in the Inconel 718 bi-cast program. These trials have provided sufficient data allowing the experimental parameters to be modified for improved bonding. Possible improvements in the bi-cast process have been identified and will he assessed in trials 7 and 8.

Specimens are being machined from bi-cast trials 4, 5 and 6 in order to perform mechanical property testing on the bonded area.

• Material Testing

— Torlon

Further specimens of the LOX compatible Torlon will be obtained for mechanical property testing.

August 1990

• Design Activities

In July, preliminary design layouts were generated for the major turbopump components and subassemblies. Instrumentation bosses and health monitoring ports, were incorporated in the design layouts. Hardware purchasing quotes for the .ADP Liquid Oxidizer (LOX) Turbopump Program Phase 11 will be estimated by vendors and Pratt & Whitney (P&W) manufacturing based on the preliminary design layouts. Also, production hardware costs will be solicited from vendors for input to the cost model.

Design layouts were reviewed by a casting vendor and P&W manufacturing engineering to suggest improvements in turbopump producibility and to reduce manufacturing labor hours and processing time. Design layouts are being changed to incorporate the suggestions from the production review.

During July, several reliability meetings were conducted to review the ADP LOX Turbopump Failure Mode Effects Analysis (FMEA) and Hazard Analysis with the designers, project engineers, and engineering support groups. The FMEA is continually being modified to reflect the current design.

— Test Impeller

The hydrodynamic airfoil definition for the impeller blade has been incorporated into the three-dimensional nodal structure analysis (NASTRAN) model. The model is being refined to include fluid pressure loads. Snap fits in the hub attachments were finalized based on the deflection results from the two-dimensional model. The casting vendor is in the process of machining the model tooling, using the impeller computer-aided design (CAD) files provided by the P&W design group.

Arbor tooling design is nearing completion. The balance plane locations were optimized for stability margin.

— Blades and Vanes

Campbell diagrams have been generated for the turbine blades and vanes. Preliminary vibration analysis indicated that the tip shrouds become excited in the operating range. Shroud thicknesses and geometry are being modified to push out the natural frequencies beyond the operating range into a low-risk region. A vibrational model is being modified to account for centrifugal load deflections which will simulate blade shape during running conditions.

— Turbine Housing

Pratt & Whitney has coordinated with the casting vendor in a continuous effort to improve the structural housing castability and to simplify the casting fabrication process. Preliminary design layouts for the inlet and exit turbine housings, backbone, and turbine inlet support are being modified to incorporate changes suggested by the casting vendor and manufacturing.

A three-dimensional NASTRAN model of the turbine inlet housing has been initiated. A preliminary airfoil cross section of the turbine exit strut has been generated. The casting vendor is studying the impacts of the strut thickness and location on the exit housing casting process. Also, computational fluid dynamic (CFD) codes are being modified to analyze the flow in the turbine volutes.

— Inducer/Impeller

After several iterations with the two-dimensional inducer model, P&W has reduced the inducer weight to improve the rotordynamics of the pump rotor critical speed while maintaining sufficient safety margin. Hydrodynamic airfoil definition for the inducer blades and impeller blades are being incorporated in the three-dimensional NASTRAN models. Airfoil thickness and taper will be iterated based on stress and defection results from the NASTRAN models.

— Pump Housings/interpropellant Seal Package

Preliminary design layouts were completed for the inlet and discharge pump housings. Fine grain Inconel 718 is the baseline material for both housings. Diffuser vanes were omitted from the pump discharge volute which eliminates a potential crack initiation point and high-stress area. Configuration modifications, which were suggested by the casting vendor to improve the casting feasibility, were incorporated in the design layouts.

At the downselect presentation, NASA requested P&W to consider amount of helium consumption as a major item when trading the Interpropellant .Seal (IPS) package. The IPS packages were re-evaluated by considering the vehicle helium system cost impacts, helium propellant costs, and the turbopump hardware cost. Life-cycle cost analysis indicated that the carbon ring seals have a cost advantage over the stepped labyrinth seals. The cost advantage is attributed to the vehicle helium system cost benefit.

- Fabrication Processes

— Impeller Technology

(Howmet) The third full-scale fine grain Inconel 718 impeller, which was cast using existing tooling, is finished with hot isostatic pressing/heat treatment and nondestructive evaluation. The impeller is being returned to P&W, along with a section of the second cast impeller, for metallurgical evaluation and material property testing.

(PCC) To implement updates in the impeller configuration, PCC has delayed the machining of the wax injection die which is used in the investment casting process. A file containing the updated configuration data points is being created and will he sent to PCC in early August. Three full-scale Inconel 718 test impellers will be fabricated; one will undergo spin testing to verify structural integrity.

— Rapid Omnidirectional Compaction

Fifteen planned sample configurations have been compacted using steel fluid dies. The steel fluid dies surround the Inconel 718 powder during the compaction process. A rough machining and chemical leaching process is required to remove the steel die. Six of the dies have been rough machined and are ready to be chemically leached.

The six dies are being, shipped to P&W. The remaining nine are more complicated and will take more time to rough machine. Upon completion of chemical leaching, dimensional and material property evaluation will be conducted to determine the feasibility of the process for fabricating a full-scale part.

— One-piece Shaft/Disk

Mechanical property testing for the Waspaloy one-piece shaft/disk has been complete by the forging vendor. To verify the material test data. additional material testing will he conducted upon receiving the hardware.

The forging of the A286 one piece shaft/disk is scheduled for completion by the end of Phase I.

—Structural Castings

The Haynes 242 casting demonstration will provide cast plates for material property investigation. These plates will provide preliminary data on the castability of Haynes 242. The plates are expected to be cast and hot isostatic pressed/heat treated in August.

Following the casting of the plates, Howmet will demonstrate the casting in a housing configuration. This demonstration will use existing tooling.

— Bi-casting

Trials seven and eight have been completed in the Inconel 718 bi-cast program. There are two trials remaining in the program.

Material testing is complete on specimens received from previous trials. Tensile and elongation data have shown that suitable properties can he obtained from the process, but further trials are needed to evaluate the ability to obtain a consistent bond across the interface. Trials seven through 10 will provide further data.

— Diffusion Bonding

There are three trials remaining for demonstrating the diffusion bonding of either Inconel or Waspaloy to a mating part of the same material. One trial, which used a nickel coating, is complete.

Specimens are being machined from previous trials without nickel interfaces. .Although the trial did not provide 100 percent bonding, the specimens will be used to determine the strength of the interface part that bonded.

- Material Testing

— Torlon

Technical problems with the specimen grips on the tensile test machine has delayed further procuring of Torlon samples. There was difficulty in grabbing the Torlon samples during the previous tensile test that were completed. Additional Torlon specimens will be ordered for testing purposes when this problem is solved.

— Stellite 31

Material property testing of Stellite 31 is complete. Testing evaluation and report documentation is underway.

— Castable Waspaloy

Both tensile and low-cycle fatigue testing of castable Waspaloy, which was completed in air and hydrogen, is finished and documented.

September 1990

- Design Activities

Design activities were directed toward incorporating manufacturing and producibility improvements suggested by the casting vendor and Pratt & Whitney (P&W) manufacturing group into the preliminary design layouts. Design configurations are being refined based on the results from structural analyses.

Both the FMEA and hazard analysis were updated to reflect the current configuration for the Advanced Development Program (ADP) LOX Turbopump. Engineering support groups reviewed the reliability analysis for the major turbopump components.

— Test Impeller

The test impeller Layout is nearing completion. Impeller blade definition was revised to reflect the current hydrodynamic definition for the ADP L02 turbopump configuration and is being incorporated into the 3D NASTRAN model for the test impeller. Computer files which describe the current hydrodynamic blade definition were forwarded to the casting vendor for incorporation into the test impeller tooling. Test impeller preload for the rig testing will be determined from structural analysis of the rotor stack-up.

— Blades and Vanes

Preliminary design layout for the turbine rotor module is nearing completion. Design of the turbine blade attachment is being modified to improve the producibility of the configuration.

The vibrational model for the turbine airfoil is being expanded to include the blade attachment area. Tip shroud thicknesses and geometry are being iterated to alleviate the higher order modes occurring near the operating range.

— Turbine Housings

Preliminary design layouts for the inlet and exit turbine housings and backbone are nearing completion. .A 3D NASTRAN model for the turbine exit housing and an integrated 3D model of all the structural housings, including the pump housings, are being utilized in the design.

— Inducer/Impeller

[Inducer and impeller 3D NASTRAN models are being refined while pressure loads across the blades are being generated for input to the structural model. This months design effort has concentrated on incorporating producibility improvement features on the layouts and calculating impeller seal clearances along the secondary flow paths.

Review of the inducer and impeller layouts by the supplier improved the component castability, including a reconfiguration of the impeller hub area to alleviate shrinkage during the casting process and relocation of datum pads for better dimensional stability.

— Pump Housings/IPS Package

A 2D NASTRAN is being constructed for both the inlet and discharge housings. The housing configurations will be iterated based on deflection results from the structural analysis.

A preliminary design layout for the IPS package is being generated which features a carbon ring seal. Alter results from a life cycle cost analysis indicated that carbon ring seals have a cost advantage, it was incorporated into the turbopump baseline configuration.

- Fabrication Processes

— Impeller Technology

(Howmet) Material property testing has been completed on a section of the second cast impeller. The test data is currently being analyzed. This section of the second impeller which was machined for specimens is being returned to P&W for further evaluation. The third full scale fine grain Inconel 718 impeller which was cast using existing tooling is finished with hot isostatic pressing (HIP)/heat treatment and nondestructive testing (NDT) evaluation. The impeller is being returned to P&W along with the remaining impeller hardware.

Full-scale plastic stereolithography impeller models have been fabricated and will be used in the place of casting dies. Two castings will be provided, one for material evaluation and the other for spin testing.

(PCC) Fabrication dies that will be used for the investment casting of three full-scale Inconel 718 test impellers are being fabricated. New files containing the updated configuration points have been implemented into the die machining process. Casting of the prototype impellers are expected in November. Three full-scale Inconel 718 test impellers will be fabricated and one will undergo spin testing to verify structural integrity.

— Rapid Omnidirectional Compaction (ROC)

All 15 planned sample configurations have been compacted using steel fluid dies. All the dies have been rough machined. Six of the dies have also been chemically leached to remove any remaining die segment. These six configurations have been dimensionally analyzed and two of the six are being prepared for heat treat and material property testing. The remaining nine configurations will also undergo dimensional evaluation and some material property testing upon completion of the chemical leaching. The dimensional and material property evaluation will be used to determine the feasibility of the process for fabricating a full scale part.

—One Piece Shaft/Disk

Results of the mechanical property testing for the fabricated Waspaloy one-piece shaft/disk have been received by P&W. In order to verify the material test data, additional material testing will he conducted upon receiving the remaining pieces of the shaft/disk which was machined for specimens.

The forging of the A286 one-piece disk/shaft is scheduled for completion by the end of Phase I.

— Structural Castings

Four plates have been cast in the Haynes 242 casting demonstration. The plates will provide preliminary data regarding the capability of Haynes 242. Before the plates are HIP,/heat treated, one plate will be used in a study to optimize the age-hardening cycle of cast Haynes 242 at the completion of this study, the remaining plates will be HIP/heat treated and used for evaluating material properties.
Following the investigation of the cast plates, Howmet will demonstrate the casting of this material in a housing configuration. This demonstration will utilize existing tooling.

— Bi-casting

The molds and inserts for trials 9 and 10 have been prepared and are ready for the bi-casting process.

These are the last two trials remaining in the program.

Trials 9 and 10 are utilizing added cast stock for the purpose of machining specimens in the perpendicular direction to those from the previous trials. Material specimen machining is being completed on the bi-cast Inconel 718 from trials 7 and 8.

Data is being analyzed to determine the repeatability of the process to produce a consistent bond with suitable properties across the forged/cast interface.

— Diffusion Bonding

Another trial has been completed using nickel coated Inconel 718. There are two trials remaining for demonstrating the diffusion bonding of both Inconel 718 and Waspaloy to a mating part of the same material. Both trails will utilize a Ni-foil interface.

The bonded sample from the previous trial is being shipped to P&W for evaluation of the bond properties.

• Material Testing

— Haynes 242

A material test matrix is being formulated for the testing of the cast Haynes 242. Machined specimens will he tested for tensile and LCF properties in the turbine housing operating environment.

Testing is expected to be completed near or after the end of Phase I of this contract.

October 1990

• Design Activities

During this report period, design activities consisted of: (1) documenting the Advanced Development Program (ADP) Liquid Oxygen (LOX) Turbopump Phase I design activities for the Packages, Requirements, and Design Review Report (DR-27), and (2) finalizing the preliminary design layouts for the drawings list, Form 1, Specifications and Microfilm (DR-29). The Hazard Analysis Report (DR-12) was delivered to the National Aeronautics and Space Administration (NASA) in September 1990.

DR-27 addresses the design and fabrication activities for the Liquid Oxygen Turbopump Phase I effort. The report describes the preliminary turbopump design in detail and the various design studies that led up to the selected design concept. In addition, component fabrication and material evaluation studies, which support the turbopump design, along with a cost model data package, are provided in the report. Integrated Product Development (IPD) has been initiated throughout the design process to ensure that producibility is built into the design and that all customer requirements are addressed. Integrated Product Development embodies the "Design to Process" philosophy plus the multifunctional team design approach to address customer requirements. The goals of IPD are to: (l) ensure that customer requirements and program needs are satisfied, (2) reduce lead time between design concept and product maturity, and (3) ensure that engineering requirements and manufacturing process performance are compatible.

—Cost Model

As part of the ADP Oxidizer Turbopump Phase I effort, P&W has completed the cost model architecture and programming approach. The cost model activities are summarized in DR-27, Section 5.0, "Oxidizer Turbopump Cost Model Data Package." In support of the ADP's common cost model requirements, NASA's comments on the cost model approach are encouraged.

- Fabrication Processes

—Impeller Technology

Tooling that will be used for the investment casting of three full-scale Inconel 718 prototype test impellers has been fabricated. The fabrication tooling should be delivered to the Pratt & Whitney (P&W) casting supplier in early October. Casting of the prototype impellers is expected in November. Three full-scale Inconel 718 impellers will be fabricated, and one will undergo spin testing to verify structural integrity.

—Rapid Omnidirectional Compaction

All 15 Inconel 718 rapid omnidirectional compaction (ROC) specimens have been chemically leached to remove the remaining steel fluid die used during compaction. The chemical leaching process, which follows rough machining, is the last step required in the fabrication process of the ROC specimens. Two parts of each configuration are undergoing dimensional evaluation to record the dimensional changes that occurred during compaction. One of each of the five different configurations has been forwarded to the materials laboratory for heat treatment and specimen machining. Room temperature and cryogenic tensile testing will be conducted on the machined specimens. The dimensional and material property evaluation will be used to determine the feasibility of the process for fabricating a full-scale part.

—One-Piece Shaft/Disk

Two A286 material one-piece disk/shaft forgings have been completed by Cameron Forge. The two forgings will be machined to a sonic shape for nondestructive testing (NDT) purposes. After vendor inspection, the forgings will be sent to P&W for a full material characterization to determine if an acceptable grain uniformity is feasible for an A 286 material part in this large size.

—Structural Castings

An age hardening cycle study has been completed on a section of one of the four Haynes 242 cast plates. The remaining three plates will now undergo hot isostatic pressing (HIP) and heat treat using the required age hardening cycle. The plates will provide preliminary data regarding the castability of Haynes 242 and whether it is technically feasible to use this material in the ADP LOX Pump turbine.

Following the investigation of the cast plates, Howmet will demonstrate the casting of this material in a housing configuration. This demonstration will use existing tooling.

— Bi-casting

The final two bi-cast trials (9 and 10) have been completed. These trials used added cast stock for the purpose of machining specimens in the perpendicular direction to those from the previous trials. Material specimen machining is completed on the bi-cast 718 from trials 7 and 8, and tensile testing is being initiated.

Data are being analyzed to determine the repeatability of the process to produce a consistent bond with suitable properties across the forged/cast interface.

— Cast-to-Size Turbine Blades

Innovative options were pursued during the course of Phase I to initiate a cast-to-size turbine blade program. This would demonstrate the capability to precision cast the turbine blade and root to eliminate machining and reduce cost. This fabrication option is no longer being considered because of technical difficulties cited by three casting houses.

Potential for this concept is promising, however, and the technology will be addressed in the Technology Development Plan.

- Material Testing

—Cast Haynes 242

A material test matrix has been formulated for the testing of the cast Haynes 242. Machined specimens will be tested for tensile and low-cycle fatigue (LCF) properties in the turbine housing operating environment.

Testing is expected to be completed near the end of Phase I.

— Cast Inconel 718 (PWA 1490)

Further testing is being conducted on cast fine-grain Inconel 718. Previous testing in a 1000°F gaseous hydrogen environment has shown that this material meets the requirements necessary for usage in the ADP LOX Pump turbine design. This material is homogenized to remove the dendritic structure common to cast 718.

This testing is required to establish the required amount of data to substantiate its usage as a turbine housing material.

- Technical Problems

Technical problems concerning the demonstration of a precision cast (net shape) turbine blade and root have not been resolved. Therefore, a net shape fabrication method is no longer a consideration for the turbine blade. A near net shape process will be used.

November 1990

- Design Activities

This report period concluded the work effort for phase I of the ADP Liquid Oxygen Turbopump Program with a preliminary design review at NASA Marshall. The following data requirements were delivered: 1) DR-05, Equipment List 2) DR-21, Safety Analysis Report 3) DR-26, Contract End Item Specification 4) DR-27, Packages, Requirement & Design Review and 5) DR-29, Drawings (level 1).

During the Phase I work effort, the PDR presentation summarized the preliminary turbopump design and fabrication activities, and the alternate configuration. The Phase II design effort will continue with the alternate configuration, featuring the L02 cooled bearing located inboard of the turbine disk. A simultaneous design effort will pursue retrofitting hydrostatic bearings into the turbopump configuration.

- Fabrication Processes

—Impeller Technology

Wax patterns, which will be used for the investment casting of the ADP prototype impellers, have been fabricated by PCC. Minor enhancements were made to the tooling to correct a small wax shrinkage effect that occurred during the first wax injection. Two patterns have been gated and are awaiting the final preparation steps before casting.

Final planning of the NDI and DVS tasks to be completed on these impellers has been accomplished by concurrent engineering teams at Pratt & Whitney. Five full-scale Inconel test impellers are being fabricated. Two castings will be poured and analyzed initially. This will determine whether modifications in the casting parameters or the gating scheme are needed to improve the casting. All five castings are required to develop the optimal casting process for this impeller configuration. Casting of the first two impellers are expected in November. The DVS tasks will include spin testing two impellers and destructively analyzing another to determine if the microstructure meets the requirements of P&W Specification 1490. This specification is being developed under the ATD program for castings requiring a fine grain Inconel 718 microstructure.

— Rapid Omnidirectional Compaction (ROC)

Eight fully heat treated tensil test specimens have been machined from the Inconel 718 parts fabricated by the ROC process. These specimens will be tested in early November. The testing will include room temperature and cryogenic environments. The samples will indicate the material properties of the ROC parts in both thin and thick sections. To date, metallurgical examinations have shown that all areas within the parts had a fully dense, fine grain structure.

A total of eleven parts were dimensionally characterized to determine the shrinkage factor and profile variation which occurs during the process. The dimensional and material property evaluation will be used to determine the feasibility of the process for fabricating a full scale part.

— One-Piece Shaft/Disk

Two A286 material one-piece disk/shaft forgings fabricated by Cameron Forge are being machined to a sonic shape. Following NDI, one of the forgings will be fully characterized through material testing and metallurgical examination. This will determine if an acceptable grain uniformity is feasible for an A286 material part in this large size.

—Structural Castings

One cast fine grain Haynes 242 housing and four cast plates are scheduled to go through the HIP (Hot Isostatic Pressing) and heat treat cycle required for this alloy. Following this treatment, the material properties of these castings will be fully characterized. The castings will provide preliminary data regarding the castability of Haynes 242. This will show whether it is technically feasible to use this material in the ADP L02 Pump turbine.

— Bi-casting

The 10 Inconel 718 bi-casting trials were completed using a forged 718 insert. The trials simulated the fabrication scenario of a bi-cast shroud onto a machined impeller blade. The objective of the trials was to yield cast 718 type properties across the bondline of the forged-to-cast interface. In trials 1 through 8, the required microstructure and material properties could not be maintained across the entire bond interface. This effect was attributed to the inability to control the required heat input needed at both the center and outer bondline during the bi-casting process. Also, no thermal control process could be identified for this demonstration or for the full-scale process required for the impellers. Because of these results and the new risks associated with developing the process for this application, trials 9 & 10 were not evaluated.

- Material Testing

Ongoing tests are being conducted to characterize cast fine grain Inconel 718 (PWA 149O) for the ALS LOX Pump turbine environment. More 1490 material has been supplied by a casting vendor. Previous testing in a 1000 F gaseous hydrogen environment, has shown that this material meets the requirements necessary for usage in the ADP L02 Pump turbine design.

This testing is required to establish the required amount of data to substantiate its usage as a turbine housing material.

November 1990

• Design Activities

Upon completion of the 18 month Advanced Development Oxidizer Turbopump Program. Pratt & Whitney (P&W) was issued an Engineering order revision which modified the contract to extend the development effort through November. The funding will support the preliminary design and fabrication activities through an interim period until the restructuring of the Advanced Development Programs and the formation of the Prototype Preliminary Design Phase.

During the month of November, P&W continued its efforts in the preliminary design of the post PDR Oxidizer Turbopump Configuration. The configuration features a one-stage turbine and a LOX cooled bearing compartment located inboard of the turbine disk. This continuing effort will include a simultaneous design effort for retrofitting hydrostatic bearings into the turbopump configuration.

• Fabrication Processes

— Impeller Technology

Final preparations are being made to pour 2 castings of the ADP prototype impellers at PCC. During this month, modifications were made to the vacuum chamber fixtures to allow for the casting of' this configuration.

Five full-scale Inconel test impellers are being fabricated. Initially, two castings will be performed and analyzed to determine whether modifications in the casting parameters or the gating scheme are needed to improve the casting. All five castings are required to develop the optimal fine grain casting process for this impeller configuration. The DVS tasks will include spin testing two impellers for growth measurements and destructively analyzing another to determine if the microstructure meets the requirements of P&W Specification 1490. This specification is being developed for castings requiring a fine grain Inconel 718 microstructure.

— Rapid Omnidirectional Compaction (ROC)

All five different geometries of ROC processed Inconel 718 powder have been evaluated. Following solution heat treatment, microstructures from nearly all selected sections exhibited a high degree of recrystallization with little or no prior powder boundaries present. The original powder had recristallized to a fine grain size of predominantly ASTM 8 with occasional isolated coarser grain areas of ASTM 6. Metallurgical examinations have shown that all areas within the parts had a fully dense, fine grain structure.

A total of 14 room temperature and cryogenic tensile tests were conducted on thin and thick sections of the ROC processed parts. The results showed consistent tensile strength properties which were comparable to wrought values. Overall, the results showed that the ROC process is a technically feasible process for fabricating the oxidizer turbopump inducer. Further development work is required to demonstrate the capability for fabricating the impeller. Preliminary estimates have shown that recurring costs for this fabrication method are slightly lower than a forged machined method while the lead times are also reduced.

Because of the reduction in program funding and the continued success of the impeller casting demonstrations, no further work is planned for this fabrication technique.

— One-Piece Shaft/Disk

Two A286 material one-piece disk/shaft forgings fabricated by Cameron Forge have been machined to a sonic shape and have completed NDI processing. A section of the disk ring will be removed for material testing by the supplier, while the remaining disk/shaft and the second full forging will be shipped to P&W. Following NDI. Full characterization through material testing and metallurgical examination will be completed on one forging to determine if an acceptable grain uniformity is feasible for an A286 material part in this large size.

— Structural Castings

One cast fine grain Haynes 286 housing and four cast plates are waiting to go through the HIP (Hot Isostatic Pressing) and heat treat cycle required for this alloy. Because of the alloys unique HIP temperature and heat treat cycle, the schedule for this processing was extended into December. Following this treatment, the material properties of these castings will be fully characterized. The castings will provide data regarding the castability of Haynes 286 and whether it is technically feasible to use this material in the ADP LOX Pump turbine.

— Hydrostatic Bearing Material Development

Preliminary investigation has begun on the selection and evaluation of LOX compatible hydrostatic hearing material. This initial analysis is being paralleled with configuration trade studies being conducted in the technology development add-on task.

- Material Testing

Further testing to characterize cast fine grain Inconel 718 (PW 1490) for the ALS LOX Pump turbine environment is being completed. Previous testing in a 1000°F gaseous hydrogen environment, has shown that this material meets the requirements necessary for usage in the ADP LOX Pump turbine design.

3.0 PHASE II SEQUENCE OF EVENTS

INTRODUCTION

During December, 1991, the efforts of this development program to support the design and development of the Space Transportation Engine (STE) LOX Turbopump were redirected. The design effort was transferred to the Space Transportation Engine Program (STEP) Phase B contract. The Phase B contract encompassed the initial design for the STE Prototype Engine components, including the LOX Turbopump, which was being developed by P&W under the agreed consortium work split.

In support of the LOX Turbopump development, the Advanced Development Program emphasis was changed to a materials development and demonstration program. The focus was on individual technologies that had the greatest potential for reducing recurring cost and increasing reliability. P&W and NASA identified and selected critical technologies that require further development and testing in fiscal 91. The technologies include; low cost fine grain material cast impeller, hydrostatic bearing development, ball bearing development, and turbine housing casting demonstration and material characterization. Other options, including pump performance (optimization water test) and material characterization for turbine blades, turbine vanes, and disk/ shaft, were identified but not considered for immediate development due to limited funding for FY 91. Following the program changes, P&W initiated the new activities required to support technology development in fiscal 91.

A supplemental agreement that deferred the original provisions of this contract was received from NASA in June of 1991. The performance of the scope of work as originally contained in the contract was deferred until restructure of the program is adequately defined. As specified by the supplemental agreement, P&W was tasked to perform the scope of work as defined by the Statement of Work, paragraph 5.4 that reads "and conduct analysis and laboratory tests necessary to assure compliance with design requirements." In particular, these analyses and tests would comply with the development of the following turbopump component technologies:

- Cast impeller demonstration
- Hydrostatic bearing development for the Lox Turbopump
- Material evaluation
- Ball bearing design, fabrication and test

The agreement also included the submittal of the following data requirements in FY91 :

- DR-01 Monthly Financial Management Report
- DR-02 Quarterly Financial Management Report
- DR-03 Monthly Progress Report
- DR-07 Propellant & Pressurant Use
- DR-08 Propellant & Pressurant Forecast
- DR-11 Accident/Incident Report
- DR-13 Contractor Documentation
- DR-14 Documentary Photographic Requirements
- DR-15 Technical Implementation Plan
- DR-16 Logic Network & Key Milestone Chart

What follows is a summary of monthly reports that covered the individual technology and material activities.

FINE GRAIN CAST IMPELLER

January - 1991
Precision Castparts Corp. (PCC) has poured two Inconel 718 full-scale test impellers. This impeller configuration closely resembles the final P&W LOX Turbopump impeller which was designed in Phase I of this ADP contract. Although both castings contained minor flaws, the casting process for this impeller configuration was successful and PCC was confident that the process could be refined to improve the casting quality. The first impeller is being prepared for display purposes, while the second impeller is undergoing analysis by PCC and P&W to determine the extent of the fine grain microstructure within the casting. Further castings are being planned in order to obtain two impellers for spin testing to determine its structural integrity at operating speeds.

February 1991
The homogenization, hot isostatic press (HIP) and solution/ precipitation hardening parameters for the fine grain cast Inconel 718 test impellers have been established and agreed upon by P&W and Precision Castparts Corporation (PCC). One impeller is being prepared for a full heat treat and will then undergo metallurgical analysis

and possible further material characterization. A second impeller was surface finished and shipped to Washington, D.C. for the hardware display at the ADP review.

Two more wax assemblies are being prepared for further castings. These castings will include datum pads that will be used for machining the impeller bore and outer surfaces. These machined impellers will be spin tested to verify operating stresses, design margins and structural integrity at operating speeds.

In a parallel effort, two spin arbors for the machined impellers are being fabricated at the P&W GEB tooling shop. These arbors are undergoing modifications to allow for strain gage wiring through the arbor assembly. Once these modifications are complete, the arbors will be inspected for dimensional accuracy.

Six strain gages will be used to form a calibrated load cell for determining the preload during assembly of the impeller on the arbor. Also, the strain gages can provide real time loading of the impeller during spin testing. In addition, studies are being conducted to determine strain gage placement for impeller critical areas.

March 1991

The fine grain cast Inconel 718 test impeller used in the ADP hardware display in Washington D.C. has been returned to Pratt & Whitney and is being used for display purposes. A second impeller has completed the pre-HIP homogenization cycle and begun the hot isostatic press (HIP) and solution/precipitation heat treatment. Following this treatment, this impeller will be inspected to determine the grain size found in various areas of the casting. Also, the impeller will be segmented and inspected to determine the dimensional variances of the blade passage walls.

Two more wax assemblies are being prepared for further castings. These castings will include datum pads that will be used for machining the impeller bore and outer surfaces. These machined impellers will be spin tested to verify operating stresses, design margins and structural integrity at operating speeds. These impellers are expected to be cast in early March.

The machining of the impeller spin arbors is complete. The arbors are in fluorescent penetrant inspection (FPI) for detection of surface flaws. After FPI, the arbors will be released to engineering for installation of strain gages. The majority of the tooling required for strain gage calibration will require a three week period to complete once the remaining tooling material is in house.

April 1991

The second fine grain cast Inconel 718 impeller has completed the pre-HIP homogenization cycle, hot isostatic press (HIP) and solution/precipitation heat treatment. The impeller is undergoing final inspection at PCC's facilities and will be sent to P&W for metallurgical analysis. Also, activity for the dimensional characterization of the cast-impellers internal passages has begun at P&W's CMM laboratory. This inspection will entail gathering points off the impeller blades, inner shroud and hub to define the walls that make up the flowpath. This data will be compared to the design data to determine the dimensional variation of the cast-to-size impeller blades. This study will also determine the capabilities of inspecting the core of an impeller in this configuration.

Another casting was attempted last month but was unsuccessful due to leakage during the pouring operation. The high pressure during the pour forced a section of the shell to separate. PCC is pursuing a different shell assembly operation which will have more structural strength in the required areas. The next casting is planned for April. If this pour is successful, two more castings will follow using the same shell assembly technique. These castings will include datum pads that will be used for machining the impeller bore and outer surfaces. These machined impellers will be spin tested to verify operating stresses, design margins and structural integrity at operating speeds.

The machining of the impeller spin arbors is complete. The arbors have completed fluorescent penetrant inspection (FPI) and dimensional inspection of the critical snap surfaces. The dimensional data of the arbor has been analyzed and input into the machining requirements of the test impeller. The tooling required for strain gage calibration is being procured.

May 1991

PCC (Precision Castparts Corporation) delivered two fine grain cast Inconel 718 impellers, representative of the ALS Lox Pump Impeller design, to P&W this month. The new shell assembly technique designed for these impellers was successful and one new impeller was poured in April. This impeller and a previously fabricated impeller were post-cast processed together. Both impellers completed homogenization, hot isostatic press (HIP) and solution/precipitation heat treatment. The delivery of these impellers marks the beginning of the validation tasks required to demonstrate the feasibility of using a cast impeller in the ALS Lox Pump. Both impellers completed full NDT at PCC.

The first impeller has been expedited to P&W's material lab for cut-up and metallography. This piece will be fully examined to determine the grain structure and grain size throughout the casting. The results of this analysis will be compared to previous subscale fine grain Inconel 718 casting demonstrations which provided fine grain microstructure and adequate mechanical properties. P&W has established a large data base of material properties for cast fine grain Inconel 718 in cryogenic conditions. This study will determine if the microstructure of these impellers meets the specifications required to utilize the previous data. Further mechanical testing can be completed if necessary to assure no variation exists between the impeller material properties and the established data base.

The second piece will remain at P&W until a purchase order is finalized with a machining vendor. A purchase order is expected to be established in early May. This impeller will machined and assembled on an arbor for spin testing. During spin test, strains will be measured and stresses determined for the critical areas of the impeller. The results of this test will be analyzed and compared to the 3-D structural model created for this impeller. The X-ray technique and results completed on this spin piece have been reviewed with P&W radiographic inspection personnel. The technique was thorough and satisfactory for this configuration. The spin piece met all requirements of a grade B quality casting per P&W specifications. The spin test is scheduled for the end of this fiscal year.

Strain gaging for the spin arbor and collar piece has been initiated. Also, fabrication of tooling required during strain gage calibration has begun. This tooling adapts the load cell to the spin arbor. Calibrating the spin arbor will ensure the proper preload is established during assembly and test.

PCC will cast two more impellers next month. One impeller will serve as a backup for the spin piece while the other will undergo further metallurgical examination to assure consistency in grain quality of these impeller castings.

June 1991
Metallurgical analysis of the first fine grain cast Inconel 718 impeller, representative of the ALS Lox Pump Impeller design, was initiated this month. This impeller was segmented and chemically etched to determine the size of the grains. Other sections of the impeller were used to machine tensile specimens for testing in room temperature and cryogenic conditions. This testing will further characterize the grain structure in the castings.

A second cast impeller has been shipped to and received by Metalex Manufacturing Inc. for machining. This impeller will be machined for assembly with the spin arbor. The impeller is expected to be complete in August.

Spin arbor fabrication is complete. Both arbors have been balanced and gaged. Upon receipt of the machined impeller, the entire spin assembly will be balanced and gaged also. Tooling required during strain gage calibration has been fabricated.

PCC is scheduled to deliver two more cast impellers. The first impeller will provide further analysis of the grain size, structure, and mechanical properties in the casting. The remaining impeller is being repair welded and heat treated for use as a backup to the spin impeller.

July 1991
Metallurgical analysis of the first fine grain cast Inconel 718 impeller, representative of the ALS Lox Pump Impeller design, was completed this month. The impeller was segmented and chemically etched to determine the size of the grains. Other sections of the impeller were used to machine tensile specimens for testing in room temperature conditions. The results of the mechanical testing showed properties exceeding requirements for the Lox Pump impeller application. Further characterization will be completed on sections from two other impeller castings.

To further optimize mechanical properties, PCC is planning to cast two additional impellers. The first of these remaining two castings will be poured in July.

Machining of the spin test impeller is continuing at Metalex Manufacturing Inc. The CNC program for machining the impeller is complete. This impeller will be machined for assembly with the spin arbor and is expected to be completed in August.

The spin arbor fabrication, which includes spin balance and load cell calibration, is complete.

August 1991
The fifth cast Inconel 718 impeller to be delivered to P&W was successfully poured during July. This pour utilized modifications in the gating from previous pours. These modifications were implemented to assure the thin shroud

is completely filled. The casting has been visually inspected and shows no defects. The casting is currently undergoing further NDI. This impeller will serve as a backup to the spin piece.

The fourth impeller was received from PCC this month. This impeller will be examined metallurgically and machined for mechanical test specimens. Testing is also being completed on material which was machined out of the spin impeller bore. This testing combined with previous tests on the second impeller will give an accurate data base for material properties.

PCC is confident the new gating scheme is the optimal for this impeller configuration. To further optimize mechanical properties, PCC is planning to cast two additional impellers.

Machining of the spin test impeller is nearly complete at Metalex Manufacturing Inc. Final grinding steps are being completed to meet the specified tolerances. The impeller is scheduled to be complete in August.

The spin arbor fabrication, which includes spin balance and load cell calibration, is complete.

September 1991
Machining of the spin test impeller is complete at Metalex Manufacturing Inc. The impeller is being shipped to Pratt & Whitney and is expected to be received in early September.
The spin arbor fabrication, which includes spin balance and load cell calibration, is complete. The date of the impeller spin test may slip into fiscal year 92.

The fifth cast Inconel 718 impeller to be delivered to P&W has completed homogenization, HIP, and heat treatment. During solution heat treatment, four small cracks formed on the leading edge of four of the six impeller blades. The cause of the cracking has been attributed to the thermal strain induced from either the furnace start up cycle or the gas quench which is used to cool the part after solution. Because the location of the cracks are very accessible, PCC is confident they can repair weld the cracks and fully inspect the welded area. Weld properties, which are generally comparable to conventionally cast Inconel 718, in this region of the impeller will be satisfactory for spin test. During future heat treat cycles, an insulator will be used to control thermal transients in the blade region. Insulation was used in the homogenization cycle and no cracks occurred in the impeller. This fifth impeller is expected to be delivered to P&W in late September. This impeller will serve as a backup to the spin piece.

The fourth impeller received from PCC has been machined to obtain specimens for tensile testing and cross sectional pieces for grain size evaluation. The specimens are being machined and currently scheduled to be tested in late September. A cross section of the impeller has been chemically etched and the grain size throughout the impeller has been determined. Approximately 60-70% of the cross section met PWA 1490 specification guidelines for grain size (ASTM 1-3). Testing is also being completed on material which was machined out of the spin impeller bore. These specimens have been machined and will be tested in early September.

PCC is planning to cast two additional impellers to further optimize grain size and mechanical properties.

October 1991

The spin test impeller, machined at Metalex Manufacturing Inc., was received this month at Pratt & Whitney. The impeller is currently undergoing FPI at P&W's Materials Engineering and Test (ME&T) Facility. Prior to spin testing the impeller, several operations need to be completed. These include; final dimensional inspection of the impeller snaps, strain gaging the impeller bore, rough balancing the impeller, strain gage installation of remaining impeller regions, detail balance, and fabrication of a new arbor nut and support tooling. The new arbor nut will allow larger preloads on the assembly and higher spin speeds during burst margin test (spin growth test).

Precision Castparts Corporation (PCC) is currently processing a fifth impeller which is scheduled for delivery in November. This current impeller has replaced the previous #5 impeller which formed cracks during solution heat treatment. The new impeller has completed initial FPI, X-ray and visual inspection. The part will undergo HIP and final heat treatment in October. This impeller will serve as a backup to the spin piece.

Material testing from the fourth impeller has been delayed and is now scheduled for October. In an attempt to improve ductility over previously tested impeller specimens, some impeller material will be resolutioned at 2000° F and age hardened to reduce delta phase content in the material. The ductility results will be compared to baseline tensile test results from the normally processed impeller material. Metallurgical analysis completed on previously tested specimens that yielded low ductility, showed considerable amounts of delta phase near the failure region. Elongation on previously tested specimens have ranged from 2.1 to 13.2%. Testing next month will determine whether modifying the heat treat parameters to minimize delta phase will improve the mechanical properties of the impeller.

In addition, a separate study is being conducted to determine the recrystallization temperature of the cast Inconel 718 fine grain microstructure found in the impellers. Additional material from impeller #4 is being heated at varying temperatures ranging from 2050 to 2175° F to determine the recrystallization temperature of the impeller fine grain structure. If the grain structure remains stable at a higher temperature than what the current PWA 1490 HIP temperature requires, then the current impeller heat treat requirements could be changed to accommodate higher temperatures during HIP. By using a higher HIP temperature (eg. 21 50F), the homogenization cycle could be removed from future processing requirements and subsequently reduce cost and procurement lead times. To date, no significant recrystallization has been found in the grain structure of any impeller analyzed by P&W.

Two additional castings are being planned in attempt to further optimize mechanical properties.

November 1991
The spin test impeller, which was received at Pratt & Whitney in September, has completed FPI. The results of the inspection showed there were no surface defects on the impeller. The impeller is now being prepared for gage installation of the bore area. Two holes have been machined through the front hub of the impeller for proper gage wiring. After installation of the bore gages, the impeller will be rough balanced, final strain gaged, and then detail balanced on the entire arbor assembly.

Design of the support tooling required for arbor assembly and disassembly is complete. Fabrication is expected to be finished in December. Also, fabrication of the new arbor nut has been initiated. The new nut will allow larger preloads on the assembly and higher spin speeds.

The fifth fine grain cast impeller to be delivered to P&W, which utilized a modified casting process to improve grain structure, developed excessive shrinkage in the blade/shroud interface after homogenization heat treatment. The casting supplier will pour additional impellers after altering the casting process in a continuing effort to provide an optimum part.

Material testing from the fourth impeller is continuing in P&W's Materials Engineering and Test (ME&T) Facility. This tensile testing will determine whether a higher solution temperature will improve ductility over previously tested specimens from impeller material solutioned at 1900° F. Also, a separate study is ongoing to determine the recrystallization temperature of the cast Inconel 718 fine grain microstructure found in the impellers. Additional material from impeller #4 1s being heated at varying temperatures to determine the recrystallization temperature of the impeller fine grain structure. If the grain structure remains stable at a higher temperature than what the current PWA 1490 HIP temperature requires then the current Impeller heat treat requirements could be changed to accommodate higher temperatures during HIP the higher HIP temperature would allow the homogenization cycle to be removed from future processing requirements and subsequently reduce cost and procurement lead times.

December 1991

Approximately 70% of the spin test impeller strain gages have been installed. Placement of the final gages and trunk leads will be accomplished after the impeller is rough balanced. The entire assembly will then be detail balanced and prepared for spin testing. Because of delays in support tooling fabrication, the spin test will take place in CY 1992. Tooling fabrication is expected to be completed in January.

In early December, the casting supplier is scheduled to pour the fifth fine grain Inconel 718 impeller to be delivered to P&W. This pour will utilize modifications in gating from previous trials. These modifications have been implemented to solve
problems encountered in two earlier castings.

Material testing and analysis from the fourth impeller has been completed by P&W's Materials Engineering. The results of these studies have shown that modifications in the HIP and heat treatment parameters from previously determined parameters for fine grain cast Inconel 718 will reduce cost and lead times while improving the metallurgical quality of the impeller. One portion of the heat treatment studies has shown that the fine grain impeller castings show no abnormal grain coarsening at temperatures greater than the previously specified HIP temperature. The new revised heat treatment will utilize higher homogenization and HIP temperatures to increase the amount of solutioning of the detrimental laves phase and HIP closure without debiting mechanical properties due to abnormal grain growth. Also, a second study has shown that specimens receiving a higher solution temperature will improve ductility over previously tested specimens from impeller material. Impeller material which received the higher solution temperature displayed a 45% increase in ductility over material machined from the same location of the casting but without the higher solution temperature. The increased ductility is attributed to the reduced amount of delta phase which was a result of the higher solution temperature. The new heat treatment requirements include the increased solution temperature. The next castings received from the casting supplier will be processed to the new homogenization, HIP, and heat treatment requirements. Tensile specimens will be machined from these castings to assure that the processing changes result in improved mechanical properties.

January 1992
Fabrication of the modified spin arbor nut is complete. The new arbor nut will allow greater preload on the assembly and higher spin speeds during burst margin tests. Also, the support tooling used for assembly and disassembly of the impeller and arbor has been completed. Preparations are being made to assemble and balance the entire impeller/arbor assembly in mid-January. Shortly after the initial balance, the final gages and trunk leads will be installed and then the assembly will be detail balanced. The initial strain survey spin test is expected to take place in early February.

In December, the casting supplier poured an additional impeller casting utilizing modifications in gating and pour weight. No significant defects were found during the initial visual inspection of the impeller. The impeller is scheduled to undergo homogenization, Hot Isostatic Press (HIP), and final heat treatment in January. The parameters for the homogenization, HIP, and heat treat cycles have been revised and corrected with the casting supplier. These changes were a result of delta phase solution and grain recrystallization studies completed in November.

Additional castings are being planned in attempt to further optimize mechanical properties.

February 1992
All preparations are complete for the strain survey spin test of the Lox Turbopump prototype impeller. A preliminary spin test concluded all activities leading up to the strain survey spin. This preliminary test rotated the impeller at speeds up to 9000 rpms. By using proximity probes on the spin shaft, the check spin verified that there was no rotation around the transverse axis and no further balance work was required. The impeller was fully gaged during the check spin to simulate subsequent tests. However, the leads to the data acquisition system were not in place. The check spin verified stability through all speed ranges planned for the strain survey. The first strain survey spin test will be conducted in early February.

An additional impeller casting was delivered from the supplier. This impeller will undergo grain analysis and material property testing for further characterization of the fine grain Inconel 718 material generated in these prototype castings.

The casting supplier is currently processing the last impeller to be delivered under the current purchase order. This impeller will undergo final heat treatment in February.

March 1992
During February, the Oxidizer Turbopump prototype cast Inconel 718 impeller was successfully spin tested to 10,560 rpm. This speed represents 122% MDC or 50% margin above the predicted stress at MDC for the 580K cycle.

The impeller was initially spun to 9000 rpm to verify stable rotation. Following the check spin, the first spin strain survey was conducted to 8800 rpm (100% RPL for 580K cycle) in early February. This survey ensured collecting adequate data should a failure occur at higher speeds. Three tests were performed to this speed and strain data was successfully collected on each run. After the initial strain surveys, several spin tests were conducted at speeds up to 10,560 rpm. Again, data collection was successful and there was no apparent distress or strain hardening. After reviewing the data for consistency, repeatability, and validity, the impeller was removed from the spin test facility and shipped to Washington for the ADP review. The impeller is scheduled to be returned to Pratt & Whitney in late March for continued spin testing. Upon return of the spin impeller, dimensional uniformity within the flow passages will be checked by measuring the volume of the individual passages by using a wax filler. This will help determine the dimensional integrity of the cast-to-size impeller blades and whether there are any inherent dimensional shifts during the casting process of an impeller of this size and configuration. The remaining spin tests includes over spinning the impeller (16-18K rpm) to estimate burst margin.

Mechanical testing and grain evaluation is being performed on cast Inconel 718 material removed from the previous impeller delivered by the casting supplier. This testing is being completed to determine whether improvements in mechanical properties are being generated due to modifications in the casting process and changes in the heat treatment parameters.

The casting supplier is currently processing the last impeller to be delivered under the current purchase order. This impeller is expected to be delivered in March.

April 1992
During March, spin test activities on the Oxidizer Turbopump prototype cast Inconel 718 impeller were delayed because the impeller was being returned from hardware displays in Washington. The impeller was returned to Pratt & Whitney in late March.

Analysis of the data collected from initial strain surveys conducted in February is continuing. The strain surveys were conducted at speeds up to 9000 and 10,560 rpm. The impeller displayed stable rotation during all phases of the spin test and displayed no apparent distress or strain hardening. The speeds tested represents 122% MDC or 50% margin above the predicted stress at MDC for the 580K cycle.

Next month, dimensional uniformity within the flow passages will be checked by measuring the volume of the individual passages. This will help determine the dimensional integrity of the cast-to-size impeller blades and whether there are any inherent dimensional shifts during the casting process of an impeller of this size and configuration. The remaining spin tests include over spinning the impeller (16-1 8K rpm) to estimate burst margin.

mechanical testing is complete on cast Inconel 718 material removed from the third metallurgical impeller delivered by the casting supplier. The object of these tests were to determine whether improvements in mechanical properties (primarily ductility) were generated due to modifications in the casting process and changes in the heat treatment parameters. The material test results showed an average increase in elongation of approximately 2.5% over previously tested impeller material. There were no significant changes in yield or ultimate strength.

Also during March, the casting supplier delivered the final impeller fabricated under the current purchase order. This impeller will serve as a backup to the current spin piece or provide material if any further mechanical testing is needed this fiscal year.

May 1992
Analysis of the data collected from the strain survey spin tests of the Oxidizer Turbopump prototype cast Inconel 718 impeller is complete. The strain surveys were conducted at speeds up to 9000 and 10,560 rpm (MDC x 1.22). The analysis included the comparison of measured strains vs. analytical predictions to determine the correlation between the actual part and the finite element model. The results of the analysis showed that all gages measured

lower strains than predicted. Maximum resulting stress for a given gage location was typically within 6 KSI of the predicted stress. The maximum measured strain was located in the splitter vane and converts into a max principal stress of 48 ksi. The results of previous tensile testing has shown that this impeller material has a room temperature yield stress of approximately 130 KSI. The last impeller to be mechanically evaluated, which featured modifications in the casting process and changes in the heat treatment parameters, exhibited an average room temperature yield stress of 134 KSI. These mechanical properties provide a large safety margin when considering the measured stresses of the impeller at 10560 rpm.

Volumetric uniformity within the flow passages of the spin impeller was checked by measuring the volume of the individual passages. The measurements indicated that there were no significant differences in volume of the various flow passages. This effort was completed to determine whether there were any inherent dimensional shifts during the casting process of an impeller of this size and configuration.

June 1992
Metallurgical analysis and strain survey spin test activities for this task are complete. This task featured the development of a fine grain cast Inconel 718 prototype impeller to demonstrate the feasibility and low cost potential for utilizing a cast impeller in the oxidizer turbopump. This effort included the fabrication of seven cast impellers, 30 mechanical property tests (across 3 different impellers), 6 strain survey spin tests, and in-depth metallurgical analysis of 2 of the 7 impellers. As a result of this development, there exists a high confidence that a cast impeller in the pump environment could meet all structural design requirements imposed from the next stages of development. However, because temporary tooling was used during the fabrication process, a complete dimensional study was not performed on these impellers. During the next stage of process development, a rigorous dimensional variance analysis will be performed on the cast-to-size blades within the impeller. Prior to this analysis, further
definition on blade geometry and allowable variances is required on the final pump configuration.

July 1992
As reported last month, all activities under this task are complete. The burst margin tests were not completed on the spin test impeller because adequate verification was provided by the strain survey spin tests.

Since this concludes the advanced development of the cast impeller, reporting of this item will be discontinued.

HYDROSTATIC BEARING DEVELOPMENT

January - 1991
Detailed plans, schedules, and requirements were established for the development of the LOX Turbopump hydrostatic bearing. Preliminary design and material studies will begin in January.

February 1991
Integrated development teams conducted conceptual design studies to evaluate configurations and options for installing hydrostatic bearings in place of the baseline ball bearing assemblies. These studies looked at the effects of envelope, flow paths, rotordynamics, and material selections. The results of these studies will provide the design guidelines for the detailed ADP experimental hydrostatic bearing design.

March 1991
Studies to evaluate configurations and options for installing hydrostatic bearings in place of the baseline ball bearings assemblies continued. This includes bearing envelope, flowrates, flowpaths, rotordynamics and material selections.

April 1991
The turbopump cross-section incorporating hydrostatic bearings was updated as a result of the latest cycle. This included redirecting the pump bearing discharge flowpath to coincide with the impeller back face bleed.

May 1991
A statement of work was submitted to the Aerojet Propulsion Division for the purpose of obtaining quotations for updating a hydrostatic bearing conceptual design for the STME oxygen turbopump. The conceptual design was previously provided by Aerojet through a separate contract. A quotation has been received and is being reviewed

June 1991
A quotation from the Aerojet Propulsion Division, for the purpose of updating a hydrostatic bearing conceptual design for use in the oxygen turbopump, has been received and reviewed. After modification, it is acceptable to

both parties and procurement has been initiated.

July 1991
Work for updating the hydrostatic bearing conceptual design for use in the oxygen turbopump has been initiated at the Aerojet Propulsion Division and is scheduled for completion this fiscal year.

August 1991
Preliminary bearing configurations are being evaluated and analyzed for the Lox turbopump hydrostatic bearing conceptual design. Internal flow data from the turbopump is being utilized by the Aerojet Propulsion Division for the analysis. Two different types of bearings are being evaluated for the design.

September 1991
Hydrostatic bearing conceptual configurations continue to be evaluated and analyzed. Information is being exchanged with the Aerojet Propulsion Division including materials, housing deflections and fits so that Aerojet can optimize bearing operating clearance in the design.

October 1991
A design review was conducted at the Aerojet Propulsion Division that covered evolution of the hydrostatic bearing design and present design status.

Consideration of a rough bearing surface showed that although the rough surface provided greater stiffness, stability goals for this turbopump could be achieved by using a smooth bearing surface that would be much simpler to manufacture. Thus, for this turbopump application, a rough surface bearing would be advantageous only if cooling flow rate to the bearing became a major concern.

Following review of the several design options, it was agreed that Aerojet and Pratt & Whitney would individually review the options and each would input their opinions within two weeks. This would include consideration of bearing stiffness level, fit of the bearing into the housing and bearing sleeve on the shaft, and cooling flow rate. The schedule was updated to show completion of the hydrostatic bearing design by the end of the first quarter in 1992. This reflected the reduction in available funding for the 1 st quarter of 1992.

November 1991
Final design of the hydrostatic bearing including bearing stiffness level, fit of the bearing Into the housing and shaft, and cooling flow rate, is being agreed to between P&W and the Aerojet Propulsion Division. The scheduled completion of the design was changed to the end of 1991 to reflect the reduction in available funding.

December 1991
Work to complete the hydrostatic bearing design by the end of 1991 continues. Aerojet is scheduled to submit a final cross section and geometry for P&W approval prior to initiating final drawings.

January 1992
Design of the retrofittable hydrostatic bearings has been completed. Detailed prints have been initiated at Aerojet, with completion targeted for February.

February 1992
Bearing detail drawing work is continuing at Aerojet. Two surface designs will be provided, smooth and rough. A circular pattern has been selected for the rough surface since it provides a greater bearing area during liftoff (knurled surface was also considered), and is simpler to manufacture.

March 1992
Detailed prints for smooth and rough surface designs are being completed by Aerojet. Final report is in process.

April 1992
Design of the retrofittable hydrostatic bearings for the oxygen turbopump was completed by Aerojet. The deliverables, design blueprints, and the final report were received March 30th. The final review was conducted by teleconference on March 31st. Since this action completes the intended design activity for this item and funding is not available for fabrication and testing, reporting of this item will be discontinued.

BALL BEARING DEVELOPMENT

January - 1991
Detailed plans, schedules, and requirements were established for the development of the LOX Turbopump ball

bearing. Preliminary design and material studies will begin in January.

February 1991
Detailed design of the ALS Oxidizer Turbopump representative ball bearings is in progress. The design is expected to be completed in February. Procurement of the ball bearings for rig testing will proceed through the remainder of this fiscal year.

March 1991
Discussions with bearing suppliers were conducted to solicit final supplier input prior to finalizing detailed blue prints. The design is now complete, but placements of orders is being delayed until the engine definition is finalized.

April 1991
Procurement of baseline ball bearings to be used for rig evaluation was initiated. Since bearings are long lead time items, procurement of slave bearings needed for the bearing test rig was also initiated.

May 1991
The baseline test ball bearing and test rig slave ball bearing designs were reviewed with the bearing suppliers. Quotations for the bearings required for test rig evaluations have been requested. Responses are expected in June.

June 1991
Responses to quotations for the baseline ball bearings for the oxygen turbopump are expected in June from the bearing supplier.

July 1991
Quotes for the ALS design bearing were received by Pratt & Whitney. Procurement will be for 6 ALS design test ball bearings and 6 rig bearings. Delivery is 14 months.

August 1991
Design drawings have been modified for procurement of the ALS design bearings. Quality requirements have been reviewed and generated. Orders have been placed for some of the raw material required for the bearing fabrication.

Procurement will be for 6 ALS design test ball bearings, Purchase Order Number F430151, and 6 rig bearings, Purchase Order Number F430149. Bearings will be procured from FAG Kugelfisher Georg Schaefer KGaA, Schweinfurt, Germany.

September 1991
During this month, a meeting was held at the bearing suppliers facility to discuss engineering requirements, schedule, and raw material delivery. Part of the engineering requirements is to develop large diameter 440C billets for the NLS bearing outer race. There is concern that the large billet does not receive sufficient work to breakup long carbide stringers. Because large surface carbide stringers are indistinguishable from other surface defects like grind bums during eddy current inspection, P&W's material lab is examining material samples in different large diameters to determine the maximum diameter billet that does not contain long carbon stringers.

October 1991
Pratt & Whitney's materials lab is continuing examination of AISI-440C material samples in different large diameters to determine the maximum diameter billet that would be less likely to contain long carbide stringers. This evaluation is expected to be completed next month and the findings will be forwarded to the bearing supplier.

November 1991
Procurement of the ball bearing continues on schedule. Examination of AISI-440C material sample in different large diameters to determine the maximum diameter billet that would be less likely to contain long carbide stringers proved inconclusive. The supplier will be required to make this determination with each batch of material.

December 1991
Procurement of the raw material for ball bearing manufacturing continues on schedule. Delivery of the 440C race material, which paces the schedule, is targeted for the 1st quarter of 1992.

January 1992
Procurement of raw material for the ball bearing races and balls continues on schedule with delivery targeted for March. The cage material, Salox, has been received at Pratt & Whitney. After inspection, it will be shipped to the bearing supplier.

February 1992
Procurement of raw material for the ball bearing races and balls continues. The material is of sufficient size to produce larger size bearings, such as 650K size, if necessary.

March 1992
The ball bearing design is being updated to reflect the increase to a 650K thrust size. Prints and information will be provided to FAG, who will then update their manufacturing layouts. This change is being coordinated to minimize the impact on bearing delivery dates. The intent is to complete the design changes before raw material is delivered to FAG in April.

April 1992
The ball bearing design has been updated to a 650K thrust size, 110 mm from the 94 mm 580k size. Changes were coordinated with FAG engineers at the Pratt & Whitney facility. FAG indicated that delivery of the initial bearings would not be impacted, since material ordered for the 580k design several months ago can be used for the 650k thrust size.

May 1992
Rotordynamic trade studies of the current STME oxygen turbopump design with 650k size bearings, illustrates the pump end ball bearing dynamic radial stiffness as a sensitive parameter to subcritical operation.

Analytical prediction for the bearing stiffness is three to four times higher than the stiffness being used based on previous experience with a smaller bearing. Thus empirical radial stiffness remains uncertain for this size bearing.

As a result, plans are being made to demonstrate the radial stiffness of a bearing similar in size, type, and speed on an existing bearing rig. This effort will be coordinated through the CDT.

June 1992
Plans to demonstrate the oxygen turbopump ball bearing stiffness in a test rig continue. ROMs for the test effort, instrumentation, and data recording are being obtained and will be presented to the CDT.

Cost estimates for the larger 650K size ball bearing have been received from FAG. The purchase order will be modified to reflect the larger bearings. Delivery date will not be affected, since the material ordered for the 580k design can be used for the 650k design.

July 1992
Plans are being formalized to demonstrate the ball bearing radial stiffness on a bearing similar to the 650K size bearing on an existing bearing rig.

CDT members inspected a P&W owned bearing test rig on June 25th to determine the amount of rig rework that would be required. Several action items were generated and it was agreed that the month of July would be used to complete the action items and determine the value of the information that would be obtained by conducting these tests.

August 1992
A CDT meeting was held at NASA-MSFC on July 29 to continue discussions on the plan for conducting a ball bearing stiffness test to verify analytical predictions. Open action items were completed and NASA personnel requested that the test program be expanded to include planned imbalances. It was agreed that the proposal to conduct the tests be completed and would include the imbalance tests as well as a rig shaft balance that had previously been agreed to.

September 1992
Cost and schedule estimates for conducting ball bearing stiffness tests to verify analytical stiffness predictions were completed and forwarded to NASA for funding consideration. The estimate included additional imbalance tests requested by NASA, rig shaft balancing and detailed hardware inspection following the initial teardown.

The procurement of the Oxidizer Turbopump design ball bearings and the rig slave bearings is occurring on schedule. Delivery of the design ball bearings is expected in mid-1993, while the rig slave bearings delivery is scheduled for early next year.

October 1992
Industrial Tetonic Bearings (ITB) was authorized to disassemble the test rig that will be used to determine ball bearing stiffness, so that the hardware could be inspected. The hardware was visually inspected by P&W and was

found acceptable for reoperation and continued testing. Bearings were provided to P&W for detailed inspection at GESP.

Procurement of the oxygen turbopump ball bearings from FAG is on schedule. Inner and outer rings are in process of being machined. Salox material, to be used for cage fabrication, passed the oxygen compatibility testing and is being prepared for shipment to FAG.

TURBINE HOUSING CASTING DEMO AND MATERIAL CHARACTERIZATION

January - 1991
The testing of cast fine grain Inconel 718 (PWA 1490) in the ALS LOX Turbopump environment is in progress and 3 cast Haynes 242 plates have been HIPed and are waiting final heat treatment. Both of these fine grain cast materials will be mechanically tested and examined against the requirements set by the ALS LOX Pump turbine environment. Upon completion of these studies, further casting demonstrations and material characterizations with the selected turbine housing material will continue.

February 1991
Further tensile testing of cast fine grain Inconel 718 (PWA 1490) in 1000 and 5000 psi hydrogen is complete. Specimens were machined from a production run hardware. This results in more realistic data than would be obtained from specifically cast test specimens. Data compilation and evaluation is in progress. Fatigue specimens of 1490 are scheduled to be tested in early February. This testing will also be performed in a hydrogen environment. Also, similar tests of cast fine grain Haynes material is planned for February.

March 1991
Further notched tensile testing of cast fine grain Inconel 718 (PWA 1490) in 1000 and 5000 psi hydrogen is complete. These specimens which were machined from production run hardware have yielded data consistent with that of specimens machined from .5 inch diameter test bars. To date, the difference between the air and hydrogen environment notch properties are not statistically significant. The maximum property degradation was observed in the notched tensile properties of production hardware specimens tested at 1 OOOF and 5000 psig hydrogen. These properties were only 3.3% lower than the properties of specimens tested in air.

Additional specimens from production PWA 1490 hardware are being low cycle fatigue tested in 1000 psig hydrogen. Previous results of LCF tests in 1000 psig hydrogen showed that the 1000F notched fatigue life of PWA 1490 was not degraded.

Smooth tensile tests (36) completed last year have also demonstrated that PWA 1490 suffers no significant debit in 1000 and 5000 psig hydrogen at 1OOOF. The mechanical properties are far beyond ALS minimum requirements. Testing conducted to date shows that PWA 1490 has excellent resistance to hydrogen embrittlement in the operating temperature range proposed for the ALS Lox pump turbine inlet and exit housings.

Full characterization of PWA 1490 is planned which will include high cycle fatigue, fracture toughness, and crack growth data. All test specimens used in the characterization will be taken from a large SSME fuel inlet housing which is very similar in structure to the proposed ALS Lox pump turbine housings. Test results will be published after completion of the characterization testing

Cast fine grain Haynes material is also being machined for test specimens. Similar screening testing will be completed on this cast material to determine its viability for use in the ALS Lox pump turbine environment.

April 1991

Specimen machining of a PWA 1490 (fine grain cast Inconel 718) structural housing has begun. These specimens will be used for further characterization of 1490 for design purposes. Characterization will include; smooth and notch tensile, smooth LCF, double notch LCF, double notch (dwell) LCF, smooth HCF, notch HCF, crack propagation, fracture toughness, and shear strength. P&W has also been soliciting the NASA material groups to determine if any additional testing is required to substantiate the usage of PWA 1490 in the turbine environment. To date, over 75 tests have been completed at the P&W materials lab and the difference between the air and hydrogen environment mechanical properties are not statistically significant. The maximum property degradation was observed in the notched tensile properties of production hardware specimens tested at 1 000F and 5000 psig hydrogen. These properties were only 3.3% lower than the properties of specimens tested in air.

Other fine grain cast materials are being screened to determine their mechanical properties in the ALS Lox Pump Turbine environment. Cast Haynes 242 and PWA 1473 (Modified Cast Inconel 718) specimens are being machined and are expected to be tensile tested in the next two months.

May 1991
Specimen machining of a PWA 1490 (fine grain cast Inconel 718) structural housing is continuing at the P&W specimen machine shop and a local machining vendor. These specimens will be used for further characterization of 1490 for design purposes. Characterization will include; smooth and notch tensile, smooth LCF, double notch LCF, double notch (dwell) LCF, smooth HCF, notch HCF, crack propagation, fracture toughness, and shear strength.

Ten notched specimens with a stress concentration factor of 6.0 have been submitted to the materials test laboratory for tensile testing. This testing will be a first look at whether PWA 1490 properties degrade in hydrogen at high Kt factors. PWA 1490 has shown no significant degradation in any previous testing using concentration factors required by design limits (2.0 and under). This testing will determine if this alloy degrades in hydrogen under the worst case conditions.

Other fine grain cast materials are being screened to determine their mechanical properties in the ALS Lox Pump Turbine environment. Fine grain cast Haynes notched specimens are expected to be tensile tested next month.

June 1991
Additional specimens machined from a PWA 1490 (fine grain cast Inconel 718) structural housing are being received at P&W. Material property tests using these specimens will be conducted during the next several months. These specimens will be used for further characterization of 1490 for design purposes. Characterization will include; smooth and notch tensile, smooth LCF, double notch LCF, double notch (dwell) LCF, smooth HCF, notch HCF, crack propagation, fracture toughness, and shear strength.

Ten notched PWA 1490 specimens with stress concentration factors between 7 and 9 have been tested in 1000 psi hydrogen at room temperature and 1000 degrees F. The preliminary results of the tests showed no degradation in properties of the notched specimens due to the hydrogen conditions.

July 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Additional PWA 1490 specimens are being machined for completing the test matrix.

August 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Additional PWA 1490 specimens are being machined for completing the test matrix.

September 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. One of P&W's hydrogen environment test rigs is down for repairs. Because of this rig shutdown, a temporary bottleneck has occurred in the hydrogen test facility and NLS specimens are not being tested at the planned rate. Baseline air testing at operating temperatures is continuing on schedule.

October 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Six specimens completed HCF testing in hydrogen during September. The testing was completed in 1000 psi hydrogen at room temperature. The data has been compared to baseline air curves formulated in the SSME-ATD program. The testing showed no significant degradation of HCF properties due to the hydrogen environment. Testing at these conditions is part of the current characterization test matrix required for design activities. Six strain controlled LCF specimens are scheduled to be tested next month. Baseline LCF testing in air is complete.

November 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature LCF testing is currently in progress. This testing includes both air and hydrogen environments.

December 1991
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature LCF testing in both air and hydrogen has been completed. Results of this testing showed minor degradation due to the 1000 psi hydrogen environment. Although minor degradation was evident, the smooth LCF life of PWA 1490 in room temperature hydrogen is acceptable. Earlier testing showed that the fatigue life of PWA 1490 is not degraded by 1000 psi hydrogen at 1000°F. The operating temperature of the turbine housings is approximately 1000°F.

Room temperature HCF testing of PWA 1490 in air is currently in progress. This testing will serve as a baseline to the room temperature HCF testing in hydrogen completed last month.

January 1992
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature HCF testing in air has been completed. This testing serves as a baseline to previous HCF tests completed in room temperature hydrogen. Results of this testing showed no degradation occurred due to the 1000 psi hydrogen environment.

Parameters are currently being determined for LCF double notch dwell tests scheduled to be tested in the first quarter of 1992. The testing will be completed in air and 1000 psi hydrogen at 1000°F. The specimens for these tests have been fabricated.

February 1992
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature tensile and 1000° HCF tests are currently being conducted in 1000 psi hydrogen. The tensile data will compliment previous room temperature tensile data obtained last year and complete that portion of the characterization matrix.

March 1992
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature tensile and 1000° HCF tests are currently being conducted in 1000 psi hydrogen. The tensile data will compliment previous room temperature tensile data obtained last year and completes that portion of the characterization matrix.

April 1992
Characterization testing of PWA 1490 (fine grain cast Inconel 718) material obtained from structural housings continued this month. Room temperature tensile testing in 1000 psi hydrogen has been completed. This tensile data compliments previous room temperature tensile data obtained last year and completes that portion of the characterization matrix. HCF testing in hydrogen is still continuing. Other tests expected to be completed this fiscal

year include crack propagation in both air and hydrogen.

May 1992
The majority of the PWA 1490 (fine grain cast Inconel 718) material characterization testing is complete. Approximately 95% of the original 147 point test matrix is complete. Remaining tests, which are planned for completion this fiscal year, include crack propagation and double notch LCF (dwell) in both air and hydrogen.

June 1992
Mechanical property testing of PWA 1490 (fine grain cast Inconel 718) material under this advanced development program is nearly complete. Room temperature crack propagation testing was completed this month. Except for 5 remaining HCF tests being conducted in the materials engineering laboratory, the crack propagation was the final test type being completed during this program segment. To date, 129 various mechanical property tests have been completed on PWA 1490.

During the testing period, several tests from the original 147 point test matrix were delayed to a later program date. Although the specimens were machined, the double notch dwell LCF testing (6 points) was delayed until cycle definition and prestart conditions are better known. The remaining fracture toughness tests (3 points) have been delayed indefinitely due to the complexity of both machining the test specimen and performing the test. One fracture toughness test in hydrogen was completed and is sufficient for preliminary design purposes. The shear tests (4 points) have been delayed until the appropriate facility modifications can be made to accommodate this type of test. The delay of these tests has reduced the original 147 point test matrix to only include 134 test points. The 5 HCF tests mentioned earlier are the last tests planned under this ADP.

July 1992
Mechanical property testing of PWA 1490 (fine grain cast Inconel 718) material under this advanced development program is nearly complete. The 5 remaining HCF specimens required for testing have been machined. Early next month, the specimens will be submitted to the materials engineering laboratory for 1000° HCF testing in air. These 5 HCF tests, which are planned for July, will mark the completion of the 134 point test matrix being completed on PWA 1490. A summary report of all testing completed under this task is currently being generated. The report will include all material property data produced from the 134 tests. This report should be completed by late August.

August 1992
Mechanical property testing of PWA 1490 (fine grain cast Inconel 718) material under this advanced development program is nearly complete. The 5 remaining HCF specimens required for testing have been machined and submitted to the materials engineering laboratory for 1000° HCF testing in air. These 5 HCF tests, which are currently being completed, will mark the completion of the 134 point test matrix being completed on PWA 1490. A summary report of all testing completed under this task is currently being generated. The report will include all material property data produced from the 134 tests. This report should be completed next month.

September 1992
Mechanical property testing of PWA 1490 (fine grain cast Inconel 718) material under this advanced development program is complete. The remaining 1000°F HCF specimen testing was completed in August. These HCF tests mark the completion of the 134 point test matrix completed on PWA 1490. A summary report of all testing completed under this task is currently being generated. The report will include all material property data produced from the 134 tests. This report is expected to be completed next month and submitted as a supplement to the next monthly report. Funding for September is limited, therefore there is a possibility that the delivery of this report will slip to November.

October 1992
Mechanical property testing of PWA 1490 (fine grain cast Inconel 718) material under this advanced development program is complete. Due to budget constraints in September, completion of the summary report documenting all test results has slipped to October. The report is expected to be completed next month and submitted as a supplement to the next monthly report.

TURBINE BLADE/VANE MATERIAL EVALUATION, SELECTION AND CHARACTERIZATION

February 1992
Material procurement and specimen machining is underway for cast nickel based alloys which have strong potential for use as turbine blade or vane material. Fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) material is being machined into test specimens for subsequent mechanical property testing. Smooth tensile, notched tensile, smooth LCF, and double notched LCF tests will be initially performed on both alloys in air and 1000 psi hydrogen at room temperature and 1 000°F. The alloys will be tested at the same

points performed on fine grain cast Inconel 718 (PWA 1490) for the turbine housing characterization. The testing will provide comparison data for all three alloys for evaluation and selection of the blade and vane material. Also, the smooth LCF and UTS of each alloy will be factored in with the coefficient of thermal expansion, coefficient of thermal conductivity, and Young's Modulus to predict the thermal shock characteristics of each alloy. Beyond thermal shock and structural property safety margins, other factors such as weldability, castability, machinability, and recurring fabrication costs will be considered during the selection process of the turbine blade and vane material.

March 1992

Material procurement and specimen machining is underway for cast nickel based alloys which have strong potential for use as turbine blade or vane material. Fine grain Mar-M-247 (PWA 1489) material is being machined into test specimens for subsequent mechanical property testing. This material is being machined from cast bellows obtained from a different program. Using material from an actual part of substantial size and diameter, gives a more representative result of the actual mechanical properties in a cast part. Conventionally cast Mar-M-247 (PWA 1447) material has been ordered in cast plates and is expected to be delivered in early March.

Smooth tensile, notched tensile, smooth LCF, and double notched LCF tests will be initially performed on both alloys in air and 1000 psi hydrogen at room temperature and 1 000°F. The alloys will be tested at the same points performed on fine grain cast Inconel 718 (PWA 1490) for the turbine housing characterization. The testing will provide comparison data for all three alloys for evaluation and selection of the blade and vane material. Also, the smooth LCF and UTS of each alloy will be factored in with the coefficient of thermal expansion, coefficient of thermal conductivity, and Young's Modulus to predict the thermal shock characteristics of each alloy. Beyond thermal shock and structural safety margins, other factors such as weldability, castability, machinability, and recurring fabrication costs will be considered during the selection process of the turbine blade and vane material.

April 1992

Fine grain Mar-M-247 (PWA 1489) material test specimens have been submitted for both smooth and double notch LCF testing. Tensile testing in air is complete on the PWA 1489 material. Hydrogen tensile testing will be completed in the following months.

HCF data in air and hydrogen of the potential alloys was determined necessary for the evaluation and selection of the blade and vane material. Consequently, HCF specimen machining has started for subsequent testing in air and hydrogen of both fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) material.

All Mar-M-247 (PWA 1447) material has been received in the form of castplates. Specimen machining for this material has begun.

May 1992
Smooth and double notch LCF testing of fine grain Mar-M-247 (PWA 1489) material continued this month . Tensile testing in air is complete on the PWA 1489 material. Hydrogen tensile testing will be completed in the following months.

Specimen machining of conventionally cast Mar-M-247 (PWA 1447) material for LCF and tensile is continuing. Mechanical testing of PWA 1447 will include the same tests performed on PWA 1489.

Last month, HCF data in air and hydrogen of the potential blade/vane alloys was determined necessary for the evaluation and selection of the blade and vane material. Consequently, HCF specimen machining was initiated for subsequent testing in air and hydrogen of both fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) material.

June 1992
Smooth LCF, double notch LCF, and HCF testing of fine grain Mar-M-247 (PWA 1489), conventionally cast Mar-M-247 (PWA 1447), and cast IN100 (PWA 658), is ongoing in the materials engineering laboratory. PWA 658 was added to the screening process after a Phase B integrated product development team decision was made to include the alloy as a potential blade material. The cast IN100 raw material was obtained and the material test process is now underway.

The material property data generated on these three alloys, in conjunction with the PWA 1490 test data and other design factors, will be used by the Phase B blade/vane integrated product development team when selecting a baseline alloy. PWA 1490 is also being considered as a blade/vane material.

July 1992
Tensile, smooth LCF, double notch LCF, and HCF testing of fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) is ongoing in the materials engineering laboratory. Material property testing of cast IN100 (PWA 658) in the turbine operating environment was delayed due to excessive centerline shrinkage in the sample material. PWA 658 was added to the screening process after a Phase B integrated product development team decision was made to include the alloy as a potential blade material. Additional material is currently being ordered and specimen machining will resume in approximately three months.

The material property data generated on these three alloys, in conjunction with the PWA 1490 test data and other design factors, will be used by the Phase B blade/vane integrated product development team when selecting a baseline alloy. PWA 1490 is also being considered as a blade/vane material.

August 1992
Tensile, smooth LCF, double notch LCF, and HCF testing of fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) is ongoing in the materials engineering laboratory. All smooth and double notched LCF air testing of PWA 1447 and PWA 1489 is complete. This LCF air testing includes approximately 36 test points on the different cast alloys. Room temperature smooth and double notched LCF testing in 1000 psi hydrogen has also been completed on PWA 1489. In addition, double notched LCF testing of PWA 1489 has been completed in 1000°F, 1000 psi hydrogen. During the next two months, the remaining LCF tests of PWA 1489 material and all LCF tests on PWA 1447 material in hydrogen will be conducted. HCF specimens for both alloys have been machined and subsequent HCF testing will be initiated next month. Cast IN100 (PWA 658) material is currently being ordered and specimen machining will begin in approximately two months. Identical mechanical property tests will be performed on the cast IN100 material for comparison to PWA 1447 & 1489.

The material property data generated on these three alloys, in conjunction with the PWA 1490 test data and other design factors, will be used by the Phase B blade/vane integrated product development team when selecting a baseline alloy. PWA 1490 is also being considered as a blade/vane material.

September 1992
Tensile, smooth LCF, double notch LCF, and HCF testing of fine grain Mar-M-247 (PWA 1489) and

conventionally cast Mar-M-247 (PWA 1447) is ongoing in the materials engineering laboratory. All smooth and notched tensile testing of PWA 1489, in air and hydrogen, is complete. Both smooth and notched air testing of PWA 1447 is complete. Tensile testing in hydrogen of PWA 1447 is expected to be completed in September. All smooth and double notched LCF air testing of PWA 1447 and PWA 1489 is complete. Also, smooth and notched LCF testing in hydrogen has been completed on PWA 1489. All hydrogen LCF testing of PWA 1447 should be completed by November. All testing is being completed at both room temperature and 1 000°F. HCF specimens for both alloys have been machined and subsequent HCF testing will be initiated next month.

Cast IN100 (PWA 658) material is currently being ordered and specimen machining will begin in approximately two months. Identical mechanical property tests will be performed on the cast IN100 material for comparison to PWA 1447 & 1489.

The material property data generated on these three alloys, in conjunction with the PWA 1490 test data and other design factors, will be used by the Phase B blade/vane integrated product development team when selecting a baseline alloy. PWA 1490 is also being considered as a blade/Vane material.

October 1992
Tensile, smooth LCF, double notch LCF, and HCF testing of fine grain Mar-M-247 (PWA 1489) and conventionally cast Mar-M-247 (PWA 1447) is ongoing in the materials engineering laboratory. All LCF and tensile testing is complete on PWA 1489 and PWA 1447, except for hydrogen testing of PWA 1447. HCF testing on both alloys is expected to be initiated in early October.

Cast IN100 (PWA 658) material is currently being ordered and specimen machining is expected to begin next month. Identical mechanical property tests will be performed on the cast IN100 material for comparison to PWA 1447 & 1489.

The material property data generated on these three alloys, in conjunction with the PWA 1490 test data and other design factors, will be used by the Phase B blade/vane integrated product development team when selecting a baseline alloy. PWA 1490 is also being considered as a blade/vane material.

DISK/SHAFT MATERIAL CHARACTERIZATION

May 1991
Plans are underway for Pratt & Whitney to characterize the A286 one piece disk/shaft forgings produced by Cameron Forge Co. Initial activities will include studying the resulting grain size and structure throughout the forging. Also, a team has been established to determine the testing required to fully characterize this alloy for the turbopump disk/shaft application. A286 alloy is the current baseline material for the disk/shaft component.

June 1991
A material development study is being undertaken with Ladish Forge Co. to produce Super A286 properties in a forged A286 bar similar in diameter to the ALS Lox Turbopump shaft. This purpose of the demonstration is to determine whether the pump end of the turboshaft can be processed (further warm worked) to create superior properties in this area of the shaft which currently requires more safety margin and added life. This task will involve warm working 4.25~ dia. forged A286 bars into Super A286 material with a reduced diameter and then applying the subsequent heat treatment. The study will include analysis of the varying zones within the forging (Super A286, A286, & transition zone).

Microstructure characterization of the A286 one piece disk/shaft forgings produced by Cameron Forge Co. has begun. Initial activities include studying the resulting grain size and structure throughout the forging. ALS characterization testing required for this alloy is being determined. A286 alloy is the current baseline material for the disk/shaft component.

July 1991
Material processing of forged A286 bars to produce Super A286 properties is scheduled to be completed at Ladish Forge Co. next month. The purpose of the demonstration is to determine whether the pump end of the turboshaft can be processed (further warm worked) to create superior properties in this area of the shaft which currently requires more safety margin and added life. This task will involve warm working 4.25" dia. forged A286 bars into Super A286 material with a reduced diameter and then applying the subsequent heat treatment. The study will include analysis of the varying zones within the forging (Super A286, A286, & transition zone).

Mechanical property testing of the A286 one piece disk/shaft forgings produced by Cameron Forge Co. is being delayed to allow for further analysis of the material content in the forging. Impurities contained in the one piece forgings may prevent this material from being tested. A decision will be made whether this material is suitable for mechanical property testing.

August 1991
Initial forging trials in support of a dual property A286 turboshaft were conducted at Ladish Co. The goal was to demonstrate warm work strengthening on the pump end of a simulated turboshaft. Conventional press forging was used to draw down 4.25" dia. recrystallized bar to the shaft envelope. Because of aggressive forging techniques, the pieces developed shear cracks during forging. Samples of bar stock for a second trial that will utilize a less aggressive forging schedule have been prepared and shipped out for a September forge date.

No further testing will be conducted on the A286 material from the one-piece disk/shaft forge trials. Integral test specimens exhibited room temperature ductility below specifications (15 to 20% elongation vs. 18% PWA 1029 minimum). This material had a marginal microcleanliness rating that may have caused the drop in ductility. Higher cleanliness standards will be used for all future material.

September 1991
The second forging trials in support of a dual property A286 turboshaft are scheduled for mid-September at Ladish Co. The goal is to demonstrate warm work strengthening on the pump end of a simulated turboshaft. Samples of bar stock for the second trial have been received by Ladish.

October 1991
The second forging trials in support of a dual property A286 turboshaft were completed in September at Ladish Co. The goal was to demonstrate warm work strengthening on the pump end of a simulated turboshaft to achieve Super A286 properties. Processing changes implemented during these trials included tapering the billet end to reduce surface stresses, limiting the amount of deformation per heating cycle to reduce buildup of high shear strains which occurred in the first trials, monitoring development of shear patterns, rotating the workpiece appropriately to allow more uniform work and using a higher temperature for the first sequence of working followed by the standard working temperature for subsequent forging steps. As a result of the process changes, the specimen bars received more cross sectional reduction and increased warm work strengthening over the previous trials. The bars will be aged per PWA 1052 and then cut up to evaluate the microstructure and RT tensile properties. Ladish will also cut

out specimen blanks for further testing at P&W.

Tensile testing is nearly complete on the bar sample that was partly worked during the first forging demonstration at Ladish Co. The results of this testing should be available in early October.

November 1991
Material property testing is finished on the Super A286 test bars fabricated during the first forging trials at Ladish Co. The goal was to demonstrate warm work strengthening on the pump end of a simulated turboshaft to achieve Super A286 properties. The process involved working a 4.25 inch diameter forged A286 bar down to the required diameter for the shaft envelope, while increasing the material properties. The process increased the strength of the material approximately 30% over typical A286 properties. Ultimate tensile strength of the processed bar ranged from 176 to 188 KSI while yield strength ranged from 148 to 157 KSI. In addition, tensile tests are being conducted on the second forging trials in which the specimen bars received more cross sectional reduction The increased warm work was an attempt to Increase strength over the 1st trials. This testing is expected to be completed in November The design of the preform for these experimental pieces was intended to prevent end cracking observed in the first trial. However, while the samples were forged to a greater reduction, cracks were not eliminated. The cracks are due to lateral spreading of the forging that leads to non-uniform strain and ultimately cracking along intensely deformed shear planes. Scale up trials will be conducted using rotary forging wherein the non-uniform strain pattern seen in the initial open die forge trials will be greatly reduced The chief benefit of rotary forging will be to provide constraint and avoid the lateral metal movement associated with open dies. Also, rotary forging should allow more consistent shaft processing from part to part. The primary method to be investigated involves GFM rotary forging equipment available in several production facilities in the U.S.

December 1991
Material testing of the Super A286 bars generated during the second forge trial at Ladish Co. has been completed. These bars exhibited a slight increase in room temperature yield strength over the first trials. Typical yield strengths for both longitudinal and transverse test directions ranged from 150 to 157 ksi. A portion of the bar which was not warm worked during the forging trial (simulating the turbine disk), will be tested to determine what impact the 1500°F heating will have on the standard A286 portion of the dual property configuration. These tests will be completed early 1st quarter of next year.

Supplier quotations for the full scale demonstration of the dual property one piece disk/shaft are expected to be received in December. Two basic one piece fabrication approaches are being considered. The first approach, which the early subscale studies were based, involves forging a disk preform with a stub shaft and then warm swaging the shaft down to the required envelope while also generating Super A286 properties. The second approach is to warm forge a starting bar to establish Super A286 and then warm upset the disk end while preserving high strength in the shaft. A key consideration for the quotations and the conduct of this development effort will be the use of carefully designed experiments that allow primary process factors to be identified and give insight as to how these factors should be controlled. The order for raw material is to be released in December.

January 1992
Final testing of the Super A286 bars generated during the second forge trial at Ladish Co. is still underway. A portion of the bar which was not warm worked during the forging trial (simulating the turbine disk) is being tested to determine what impact the 1500°F heating will have on that standard A286 portion of the dual property configuration. Air testing completed on this material in December has shown that the properties of the standard A286 material do not degrade due to the 1500° exposure. Similar tests using specimens from the same material are being completed in a hydrogen environment to determine if there are any significant debits. These tests will be completed early 1st quarter of next year.

Supplier quotations for the full scale demonstration of the dual property one piece disk/shaft have not been received. Two basic one piece fabrication approaches are being considered. The first approach, which the early subscale studies were based, involves forging a disk preform with a stub shaft and then warm swaging the shaft down to the required envelope while also generating Super A286 properties. The second approach is to warm forge a starting bar to establish Super A286 and then warm upset the disk end while preserving high strength in the shaft. A key consideration for the quotations and the conduct of this development effort will be the use of carefully designed experiments that allow primary process factors to be identified and give insight as to how these factors should be controlled.

February 1992
Purchase orders for the full scale demonstration of the dual property one piece disk/shaft are expected to be placed in early February. Two basic one piece fabrication approaches are being considered. The first approach, which the early subscale studies were based, involves forging a disk preform with a stub shaft and then warm swaging the

shaft down to the required envelope while also generating Super A286 properties. The second approach is to warm forge a starting bar to establish Super A286 and then warm upset the disk end while preserving high strength in the shaft.

March 1992

Purchase orders for the full scale demonstration of the baseline A286/SA286 dual property one piece disk/shaft have been placed on hold until rotor stack and 650K resizing studies are completed on the STE Oxidizer Turbopump. These studies, being completed in the STE Phase B program, are examining rotor stack scenarios using A286/SA286, Waspaloy, and IN100 as the disk/shaft material. Upon completion of these studies, ADP direction will be reestablished for material development of the one-piece disk/shaft.

Material testing is continuing on baseline A286 and backup Waspaloy disk material machined from previous demo pieces fabricated in 1991. The objective of these tests is to examine effects of 1 000°F/1000 psi hydrogen on the mechanical properties of the baseline A286 material which received super processing exposure and the Waspaloy material which exhibits a beneficial necklace grain structure in the outer disk.

April 1992

- Disk/Shaft Material Characterization

Purchase orders for the full scale demonstration of the baseline A286/SA286 dual property one piece disk/shaft are still on hold pending further rotor stack and 650K resizing studies on the STE Oxidizer Turbopump. Current study results show the upsizing of the STME to 650k increased the oxidizer turbopump pump bearing radial load and resulted in higher than acceptable bearing/shaft mounted hoop stress. As a result, the shaft material will require a change to one with a lower coefficient of expansion. One of the materials being considered to replace A286/SA286 as the baseline material is Waspaloy.

Because of this consideration, Waspaloy material testing in both air and hydrogen is being accelerated to determine hydrogen debits on material properties in the disk/shaft operating environments. This testing will include smooth and double notched LCF tests at room temperature and 1 000°F.

May 1992

Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. This testing will include smooth and double notched LCF tests at room temperature and 1000°F. Waspaloy, along with IN100, is being considered as the baseline disk/shaft material since the use of A286 in the 650K design resulted in higher than acceptable bearing/shaft mounted hoop stress.

June 1992
Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. This testing will include smooth and double notched LCF tests at room temperature and 1000°F. Waspaloy, along with IN100, is being considered as the baseline disk/shaft material since the use of A286 in the 650K design resulted in higher than acceptable bearing/shaft mounted hoop stress.

July 1992
Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. This testing will include smooth and double notched LCF tests at room temperature and 1 000°F. Waspaloy is being considered as the baseline disk/shaft material since the use of A286 in the 650K design resulted in higher than acceptable bearing/shaft mounted hoop stress.

Plans are now underway for the forging demonstration of a full scale Waspaloy one-piece disk/shaft. The goals of this program will be to produce a full scale demonstration sample and to map out the process window so that important process variables are understood and production viability is insured. Development/demonstration of a high strength shaft will proceed in two phases. Phase one will be used to evaluate two potential methods and focus on feasibility and process sensitivity. Phase two will apply the preferred process method to the production of two full scale articles. These components will reflect the latest 650K design. One of the fabricated disk/shaft components will be cut up for characterization.

August 1992
Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. The mechanical properties of Waspaloy in 1000 psi are expected to be adequate for applying to the one-piece disk/shaft in the oxidizer turbopump. Double notched LCF tests at room temperature and 1 000°F is complete in both air and 1000 psi hydrogen. Smooth LCF testing at these

conditions is expected to be completed in August. Waspaloy is being considered as the baseline disk/shaft material since the use of A286 in the 650K design resulted in higher than acceptable bearing/shaft mounted hoop stress.

Plans are now underway for the forging demonstration of a full scale Waspaloy one-piece disk/shaft. The goals of this program will be to produce a full scale demonstration sample and to map out the process window so that important process variables are understood and production viability is insured. Development/demonstration of a high strength shaft will proceed in two phases. Phase one will be used to evaluate two potential methods and focus on feasibility and process sensitivity. Phase two will apply the preferred process method to the production of two full scale articles. These components will reflect the latest 650K design. One of the fabricated disk/shaft components will be cut up for characterization.

September 1992

Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. Smooth, strain controlled LCF tests at room temperature and 1 000°F are complete in both air and 1000 psi hydrogen. The remaining LCF testing is expected to be completed in September. Waspaloy has been chosen as the baseline disk/shaft material since the use of A286 in the 650K design resulted in higher than acceptable bearing/shaft mounted hoop stress.

A purchase order was placed in August for the forging demonstration of a full scale Waspaloy one-piece disk/shaft. The goals of this program will be to produce a full scale demonstration sample and to map out the process window so that important process variables are understood and production viability is insured. Development/demonstration of a high strength shaft will proceed in two phases. Phase one will be used to evaluate two potential methods and focus on feasibility and process sensitivity. Phase two will apply the preferred process method to the production of two full scale articles. These components will reflect the latest 650K design. One of the fabricated disk/shaft components will be cut up for characterization.

October 1992

Waspaloy material testing in both air and hydrogen is being conducted to determine hydrogen debits on material properties in the disk/shaft operating environments. Due to an overload of jobs in the materials laboratory, no material testing was completed on Waspaloy this month. Smooth, strain controlled LCF tests at room temperature and 1000°F are complete in both air and 1000 psi hydrogen. The remaining LCF testing is expected to be

completed in October.
A purchase order was placed in August for the forging demonstration of a full scale Waspaloy one-piece disk/shaft. The goals of this program will be to produce a full scale demonstration sample and to map out the process window so that important process variables are understood and production viability is insured. Development/demonstration of a high strength shaft will proceed in two phases. Phase one will be used to evaluate two potential methods and focus on feasibility and process sensitivity. Phase two will apply the preferred process method to the production of two full scale articles. These components will reflect the latest 650K design. One of the fabricated disk/shaft components will be cut up for characterization.

Phase one has been initiated with Cameron Forge. Subscale forging trials are planned for October. These trials will focus on the process variables of two potential forging methods for the one-piece disk shaft.

CORNER SEAL RIG

June 1992
Fabrication of the comer seal water rig and several candidate seal geometries is complete. Water flow testing has been initiated on the baseline seal configuration. This rig testing is expected to continue through July. The data obtained from this testing, along with CFD models, will be used to determine the comer seal design and optimize thrust balance.

July 1992
Fabrication of the comer seal water rig and several candidate seal geometries is complete. Twelve candidate seal geometries are slated for water flow testing to determine the optimum seal geometry. A parametric design study is being employed to determine the controlling geometric features for minimum flow leakage. During the month of June, eight candidate seals were water flow tested and data is being compiled. A motion picture video showing the flow characteristics within the water rig was sent to NASA personnel at MSFC.

August 1992
Twelve candidate seal geometries are slated for water flow testing to determine the optimum seal geometry. A parametric design study is being employed to determine the controlling geometric features for minimum flow leakage. During the month of July, three more candidate seals were water flow tested and data is being compiled.